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SAMSO TR 74-183

GLOBAL POSITIONING SYSTEM (GPS) FINAL REPORT

PART II

VOLUME C
Control Segment Trades and Analyses

Contract F04701-73-C-0296

new - see AD 921 752

Submitted to:
DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS ORGANIZATION (AFSC)
P.O. Box 92960, Worldway Postal Center
Los Angeles, California 90009

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Palo Alto, California 94303

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SAMSO TR 74-183

WDL Technical Report 5291
28 February 1974

GLOBAL POSITIONING SYSTEM (GPS)
FINAL REPORT

PART II - VOLUME C
CONTROL SEGMENT TRADES AND ANALYSES

Contract F04701-73-C-0296

Prepared for

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS ORGANIZATION (AFSC)
Los Angeles, California 90009

ATTN: YEEU

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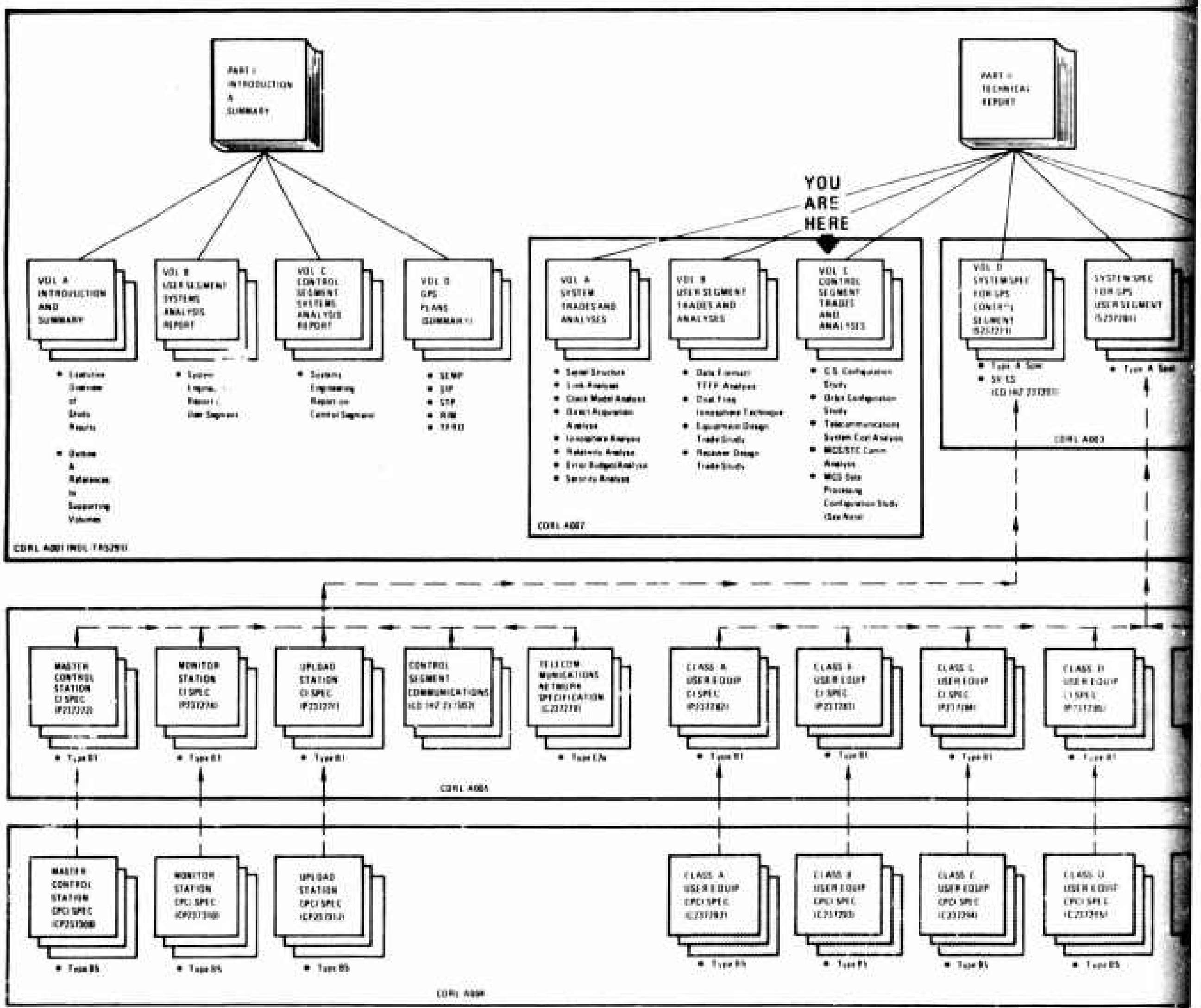
PHILCO-FORD CORPORATION
Western Development Laboratories Division
Palo Alto, California 94303

FOREWORD

This is Part II, Volume C, of the GPS Definition Study Final Report, submitted by Philco-Ford, in accordance with Sequence Number A002 of Exhibit A to Contract F04701-73-C-0296. The period of performance for the report submitted herein is from 28 June 1973 to 28 February 1974. The following figure identifies the structure of the Final Report and the relationship of this volume to the other volumes in this submittal.

WDL-TR5291
Part II
Volume C



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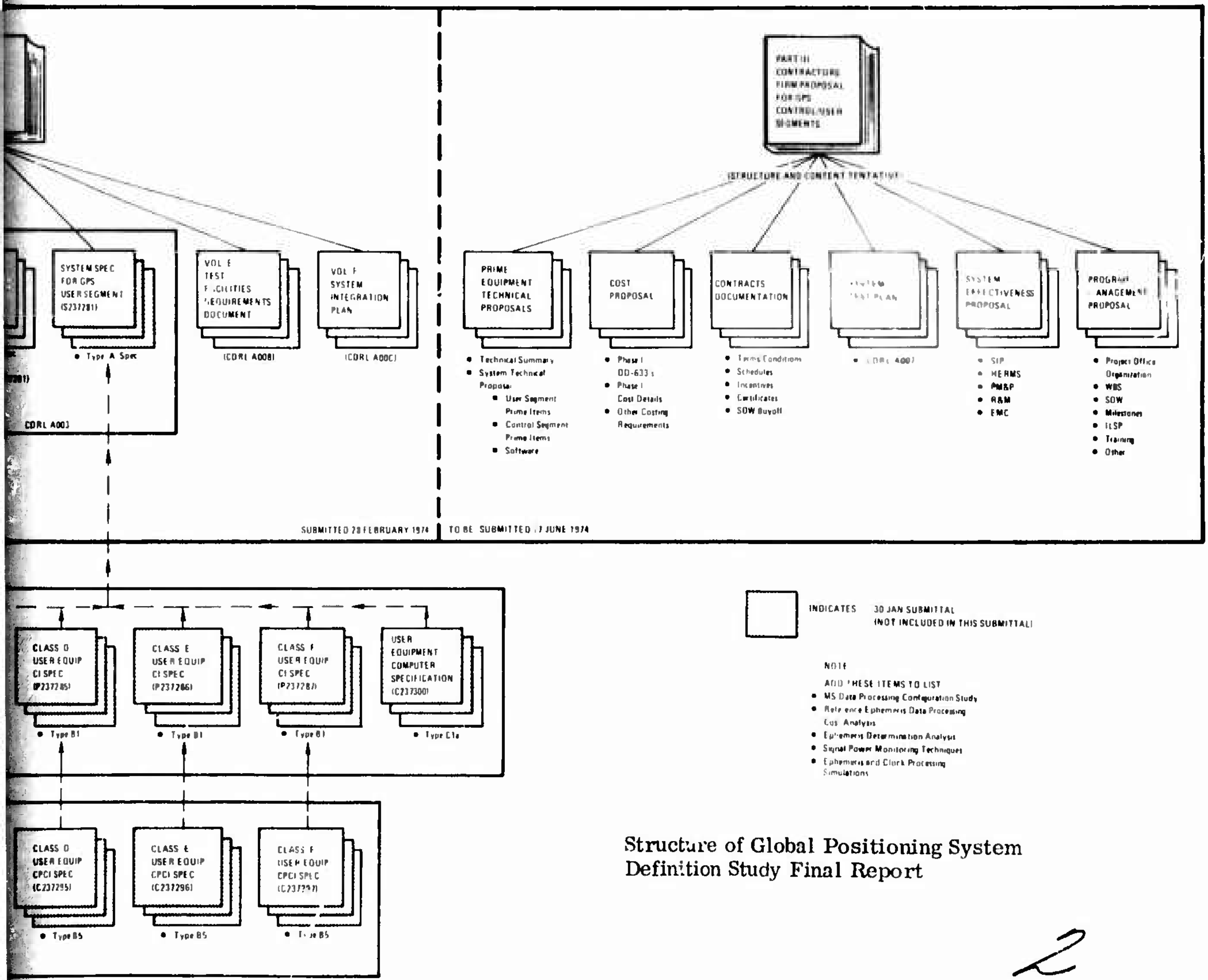

Structure of Global Positioning System Definition Study Final Report

2

PART II VOL. C
CONTROL SEGMENT TRADES AND ANALYSIS

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NOTE: Each individual report contains a detailed Table of Contents for that report.

PART II, VOLUME C

CONTROL SEGMENT

TRADES STUDIES AND ANALYSES

SUMMARY OF REPORTS

Report C1 Control Segment Configuration Study

Scope. The purpose of this trade study was to determine the optimum Phase I Control Segment configuration for the GPS. The Control Segment comprises the satellite tracking, communication, system calibration, ephemeris determination, navigation data processing, CS control and monitoring, data upload, and status monitoring functions. The study considers the impact of Phase II and III requirements upon the alternative configurations. The evaluation criteria are: Phase I, II, and III recurring and nonrecurring costs, legacy, system accuracy, functional time-line conflicts, vulnerability, implementation schedule, and cost risks and potential utilization conflicts for shared equipment. Existing facilities considered for use by GPS were: SCF, NAG, SAC, and NWL. It has been assumed that the reference ephemeris would be generated weekly at the NWL facility in Dahlgren, Virginia. Upload and verification techniques were also evaluated.

Results. The study concluded that the baseline system described in detail in the System Analysis Report, Part I, Volume C, was optimum from the standpoint of Phase I cost. Although not included in the baseline, the use of the S-band downlink for upload verification provides better security and minimizes the SCF support requirements. The use of SCF facilities minimizes the Phase I implementation costs; however, this approach has higher total costs through Phase III than a dedicated equipment approach implemented after Phase I.

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Report C2 Orbit Configuration Study

Scope. The objective of this trade study was to determine the optimum orbit for each of the GPS phases. Factors considered during Phase I are GDOP and time-in-view at White Sands Missile Range (WSMR), satellite elevation angle, station-keeping requirements, and upload time provided. Factors considered during Phase IIA are GDOP and continuous time in view of four satellites at WSMR. Phase IIB considered the requirement to provide two satellites coverage world-wide. Phase III requires four useable satellites on a global basis. Over 100 possible orbit configurations were computer analyzed.

Results. The optimum Phase I orbit configuration was the SIGMA configuration which provided time at White Sands Missile Range of 2 hours 25 minutes with an average GDOP of 4.2. The Phase IIA choice was a subset of the optimum Phase III orbit configuration, the OMEGA-2A configuration. The Phase IIB choice was a subset of the 3 x 9 GAMMA configuration, studied earlier: the 3 x 3 subset designated GAMMA-2B. The Phase III selection was the 3 x 8 configuration, OMEGA.

Report C3 Telecommunications System Cost Analysis

Scope. The annual costs of various telecommunications facilities are examined in this study. The analysis was directed toward potential Master Control Station and Monitor Station sites. Included in the analysis are costs for dedicated lines, dial-up lines, WATS lines, and shared NAG lines. The analysis is composed of two areas. The first area compares the various telecommunication links with respect to the different potential line types. Within this area, the shared NAG lines approach is examined in further detail. The second area examines the dial-up annual costs as a function of several store-and-forward intervals of time.

Results. The recurring telecommunications costs of the systems are dependent upon the frequency with which the Monitor Station (MS) data is forwarded to the MCS. If it is forwarded once per hour (baseline approach), dial-up line costs are only slightly less costly than dedicated lines. There is little advantage to data compression at the MS during Phase I. Telecommunication costs during Phase III can be relatively high. Data compression at the site is the most effective technique for reducing these costs, and is particularly effective if coupled with a reduction in the frequency of data forwarded to the MCS.

Report C4 Master Control Station/Satellite Test Center Communications Analysis

Scope. The trade study evaluates four alternative methods of communications between the Master Control Station and the Satellite Test Center. No attempt is made by this report to recommend any individual option, but rather to discuss each alternative with emphasis on the following points: (a) communication line security (b) bird-buffer security, (c) personnel requirements, (d) STC space, (e) new equipment required, (f) existing equipment, (g) software, (h) cost.

Results. The use of a dedicated bird buffer (BB) at the STC to handle all GPS coordination is the least expensive, but creates serious scheduling and reliability problems. Adding communications switching equipment that allows the MCS to be connected to any BB relieves this problem, but may present a security problem. The installation of a new dedicated tape transport and miniprocessor is the highest cost approach, but presents the least risk.

Report C5 MCS Data Processing Configuration Study

Scope. This trade addresses the general computer configuration to be employed at the MCS for Phase I of GPS. Specifically, the issue being considered is whether it uses a single integrated processor or separate processors for on-line control functions and navigation support functions.

Results. Addition of a realtime processor to the MCS to handle communications and status monitoring functions improves overall MCS availability by about 0.5%. Availability for communications and status monitoring support is improved by about 0.1%. However, the increase of about 7% in hardware cost and about 32% in software cost outweighs this small increase in availability. Even without the realtime processor, MCS availability is expected to far exceed Phase I goals. The recommended configuration for Phase I uses a single processor for all MCS functions.

Report C6 Monitor Station Data Processing Configuration Study

Scope. This trade study addresses the general processor configuration for GPS Monitor Stations (MS). Specifically, it considers whether and how to employ the user equipment processor in the MS configuration.

Results. Sharing the user equipment processor for MS functions and user equipment functions involves relatively high cost, high risk, and low legacy. Using a separate processor, eliminates the high risk factor, and increases legacy. However, it also increases cost. Removing the user equipment processor provides relatively low costs, lower risk, and higher legacy.

The recommended configuration employs a Monitor Station processor, selected to be functionally/electrically compatible with the user processor, but also to satisfy MS requirements. This processor is compatible with the user equipment receiver. The processor is removed from the user equipment group, and the required subset of its functions implemented on the monitor processor.

Report C7 Reference Ephemeris Data Processing Cost Analysis

Scope. This report analyzes the cost impact of reference ephemeris generation, particularly the cost and flexibility differences between sizing the MCS processor to generate the reference ephemerides and sizing the MCS processir to utilize an outside service (such as NWL) for the reference ephemeris production.

Results. The conclusions reached in this analysis show that the lease/buy decision is quite sensitive to the safety margins applied to Phase I instruction requirements. If the assumed margin of 75% were reduced to 0%, the conclusion could be reversed. The results are also sensitive to the time required to run the program. More refined estimates shall be generated before committments are made.

Report C8 Ephemeris Determination Analysis

Scope. The ephemeris and clock model determination software is required to translate pseudoranging data into estimates of satellite position and clock state in such a manner that system design goals related to ephemeris and clock contributions to user geoposition accuracy can be met. Considerations, related to legacy, cost, technical risk, and the utilization of Government resources are also of prime importance. The basic concepts considered applicable in being able to meet those design goals were:

a. Simultaneous multisatellite processing concept and
b. A distributed processing concept.

In addition, several different methods of implementation of those concepts were considered, related to the applicability of existing software, filter techniques, and data management.

Results. Through simulations and other related analysis, it has been shown that the distributed processing concept produces user navigation accuracies that are competitive with those of the simultaneous multisatellite processing concept, yet, have unique computational advantages, particularly, on the GPS problem. In addition, lower implementation costs with a minimum of technical risks are achieved. Recursive processing methods were chosen on the basis of their increased flexibility in being able to incorporate clock state noise.

Report C9 Ephemeris and Clock Processing Simulations

Scope. The simulations discussed in this report were conducted to determine the ephemeris contribution to the User Equivalent Range Error (UERE) and to ascertain its sensitivity to various parameters which could affect the system accuracy. The baseline system configuration was employed and orbit and Control Segment uncertainties assumed. The ephemeris representation technique was also analyzed to determine the optimum approach in terms of user processing complexity, message length, accuracy, and fit interval.

Results. A distributed processing concept utilizing range data from a station whose clock is designated as "master", and range-difference data from all other stations to determine satellite ephemerides and satellite clock-state parameters has been extensively simulated using the TRACE 66 program. Where the designated station is the more northerly of the several tracking stations considered (i.e., Alaska), the contribution of ephemeris and clock-state determination errors to UERE is 9 feet, two hours after update. The largest single contributor to this error is the introduction of station location errors of 10 feet in each coordinate, and these errors are expected to be

reduced significantly as the system matures into later phases. While TRACE-66 does not have the capability to simulate the second step in the baseline distributed processing concept, the interrelationships of all ground clocks with satellite clocks will give a derived accuracy no worse, and may be significantly better than the results reported here.

Moving the location of the fourth MS from northeastern USA to Guam did not reduce UERE over WSMR, although global performance remote from CONUS was improved, as expected. Eliminating the fourth MS altogether increased the UERE at WSMR to 11.1 feet. By designating VAFB as the ranging station with "master" clock status (in a software sense), the UERE contribution due to ephemeris and clock-state determination, at WSMR two hours after update, was predictably reduced to less than five feet, although global performance was degraded somewhat by poorer distribution of the ranging data processed.

Report C10 Signal Power Monitoring Techniques

Scope. The report describes the use of star flux and a man-made test signal, both having known intensity, for determination of received power.

Results. Receiver output powers or the AGC voltages developed by receiving the signal of unknown power are compared to the corresponding parameter signal, and the power level of the unknown can then be determined. The report emphasizes that the actual satellite power can merely be inferred from a measurement of received power at the ground station because of unpredictable variable uncertainties in the power measurement.

REPORT C 1

CONTROL SEGMENT CONFIGURATION STUDY

REPORT C 1

CONTROL SEGMENT CONFIGURATION STUDY

TABLE OF CONTENTS

CONTROL SEGMENT CONFIGURATION STUDY

1.0 SCOPE

The purpose of this trade study is to determine the optimum Phase I control segment configuration for the GPS. The control segment comprises the satellite tracking, communication, system calibration, ephemeris determination, navigation data processing, CS control and monitoring, data upload and status monitoring functions. The study considers the impact of Phase II and III requirements upon the alternative configurations. The evaluation criteria are: Phase I, II, and III recurring and non-recurring costs, legacy, system accuracy, functional time line conflicts, vulnerability, implementation schedule and cost risks and potential utilization conflicts for shared equipment.

Existing facilities considered for use by GPS were:

Satellite Control Facility	(SCF)
Naval Astronautics Group	(NAG)
Strategic Air Command	(SAC)
Naval Weapons Laboratory	(NWL)

It has been assumed that the reference ephemeris would be generated weekly at the NWL facility in Dahlgren, Virginia.

The material in this report is essentially a compilation of data presented at various meetings during the conduct of this contract. A brief amount of introductory material is given in each section to clarify the progression of thought.

2.0 Study Approach

The approach taken in the Control Segment Configuration Study is shown in Figure 2-1. The basic system requirements by program phase are established and employed to generate alternative network configurations. These are then evaluated on the basis of cost and performance. The results are then fed back and each network is altered to optimize its characteristics. The revised networks are again evaluated. This process was completed three times during the course of the study.

Figure 2-2 shows the analysis and redirection cycles which occurred. At contract turn-on, the system was required to support a rotating Y satellite configuration. During October 1973, the satellites were changed from synchronous orbit to a 12 hour period. Alternative Control Segment configurations were then developed, evaluated and a recommended approach was selected. This recommended configuration was based upon the use of Vandenberg AFB as the Master Control Station. This step is described in Section 5.1. Philco-Ford was then redirected to use NAG facilities as a baseline with the SCF as an alternative. Five configurations were then developed, three based upon NAG and two upon the SCF. The baseline system was also defined in greater detail. The results of this analysis were presented at the January 8, 1974 meeting and are contained in Section 5.2. The alternatives were then slightly revised and the baseline design extended. The new material was then presented on January 30, 1974. This is given in Section 5.3. Subsequently redirection was received that VAFB was to be the baseline MCS and US.

Tables 2-1, -2, and -3 summarize the candidate configurations as they varied during the program.

Figures 2-3 and -4 show the evaluation criteria used in the selection of the optimum configuration and the effect of varying the degree legacy desired.

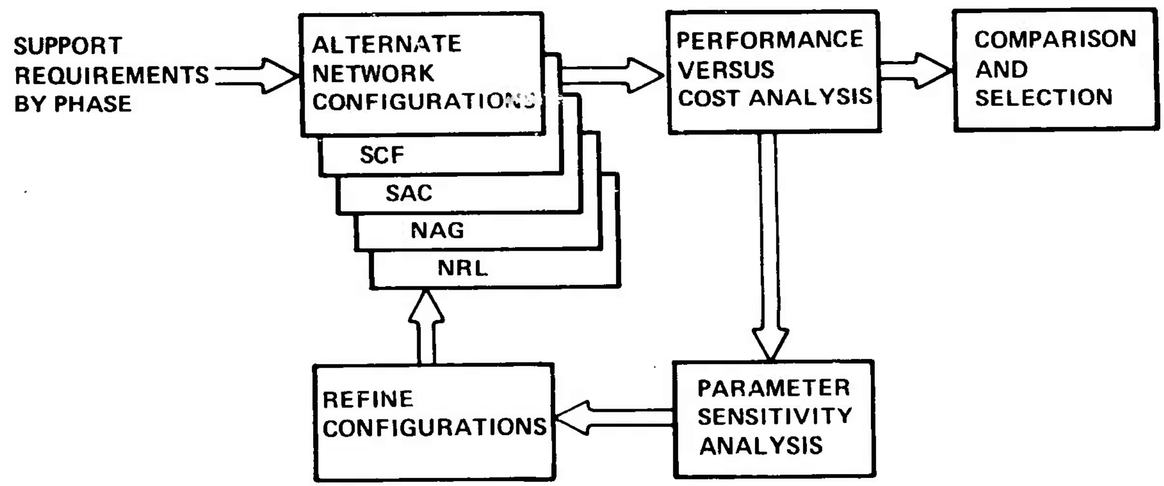

FIGURE 2-1

CONTROL SEGMENT CONFIGURATION STUDY

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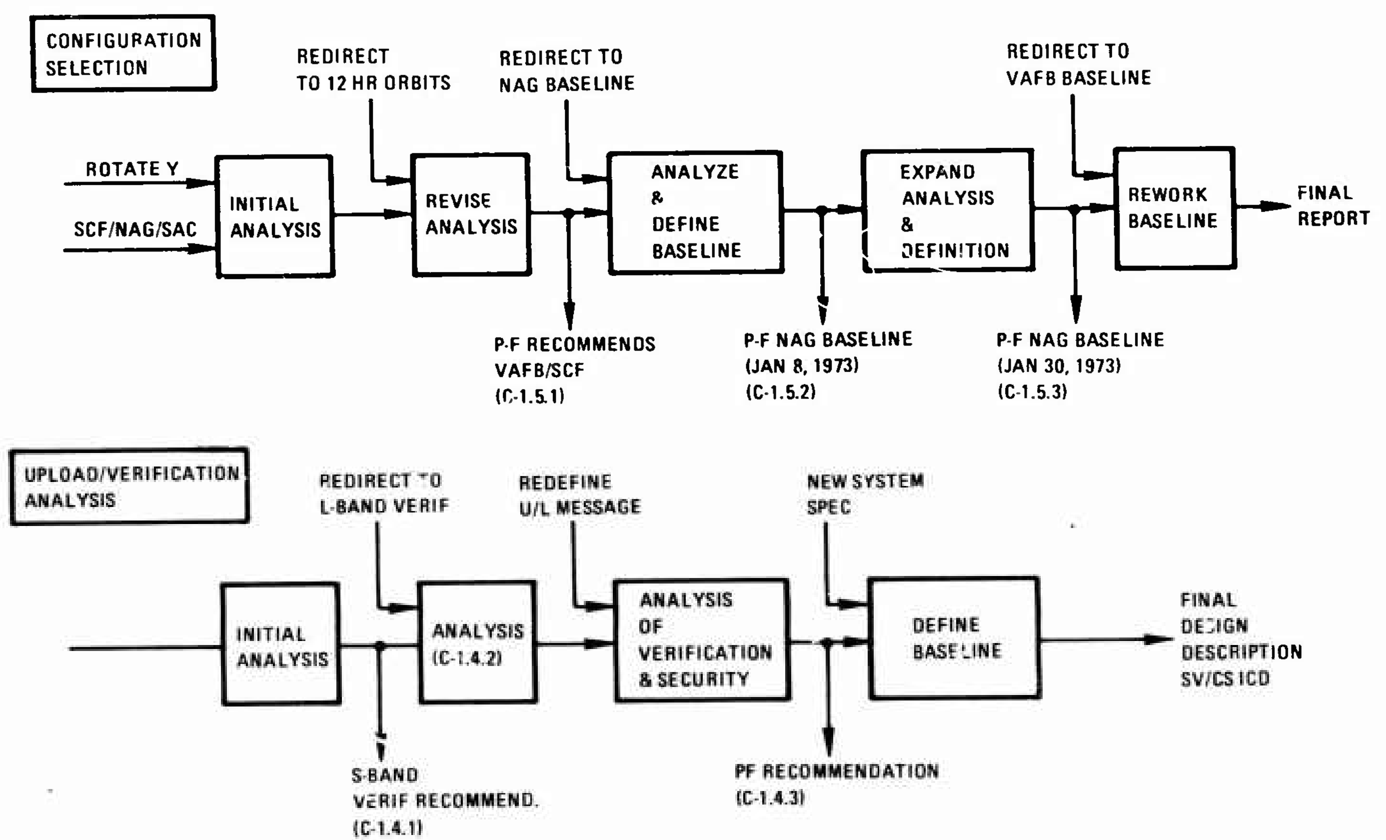


FIGURE 2-2 SELECTION APPROACH

TABLE 2-1 SUMMARY OF INITIAL CONFIGURATION ALTERNATIVES

	SCF-1	SCF-2	NAG	SAC	NWL
MCS	STC	VAFB	MUGU	OMAHA	DAHLGREN
U/L	KTS	VAFB	MUGU	FAIRCHILD AFB	VAFB
MON	KTS, VTS, HTS, NHS	KTS, VAFB, HTS, NHS	MUGU, MAINE, HAWAII, MINN.	FAIRCHILD, LORING, GUAM, OMAHA	VAFB, VIRGINIA FLORIDA, SAMOA

Table 2-2 Candidate Configurations - January 8, 1974

STATION \ ALTERNATE	A	B	C	D	E
MASTER CONTROL STATION (MCS)	STC	STC	MUGU	MUGU	MUGU
UPDATE STATION (UDS)	*KTS	ELM	SPO	ELM	*MINN
MONITOR STATIONS					
NO. 1	HTS	HTS	*HAW	*HAW	*HAW
NO. 2	NHS	NHS	*MA	*MA	*MA
REMOTE COMPUTING FACILITY (RCF)	NWL	NWL	*NWL	*NWL	*NWL

KEY: NEW / USED; DEDICATED / SHARED

*COMM FROM MCS TO

TABLE 2-3 Candidate Configuration - January 30, 1974

ALTERNATE / FUNCTION	A1	D1	D2	D3	D4	D5	
MASTER CONTROL STATION	MUG	MUG	MUG	MUG	MUG	MUG	
MONITOR STATIONS ①	MINN*	ELM	ELM	ELM	ELM	MINN*	
ULS STATION	KTS*	ELM	ELM	ELM	ELM	KTS	MINN
MCS/ULS INTERFACE	STC/BB	NEW	NEW	NEW	NEW	SAME AS A1	* SAME AS D2
UPLOAD TECHNIQUE	EXISTING SCF PRACTICE	INC SCF SECURE WORD	CS SECURE WORD	CS SECURE WORD	CS SECURE WORD		
VERIFICATION LINK	SGLS	L-BAND	L-BAND	SGLS	SGLS		
ULS SGLS RCVR	YES	NO	NO	YES	YES		
CMD GEN SOFTWARE AT	KTS	ELM	MCS	ELM	MCS		
K1-23	KTS	SCF	MCS	ELM	MCS		

① ALL CANDIDATES HAVE MONITOR STATIONS AT MUGU*, MAINE*, HAWAII*
* SHARE EXISTING COMMUNICATIONS

COST	VERSUS	PERFORMANCE
HARDWARE DESIGN & DEVELOPMENT (H)		ACCURACY
SOFTWARE DESIGN & DEVELOPMENT (S)		UPLOAD TIME
SYSTEM ENGINEERING & INTEGRATION (I)		VULNERABILITY
COMMUNICATIONS (C)		AVAILABILITY
PERSONNEL (P)		TECHNICAL RISK
LOGISTICS (L)		
DATA PROCESSING (D)		

LEGACY

Figure 2-3 Evaluation Criteria

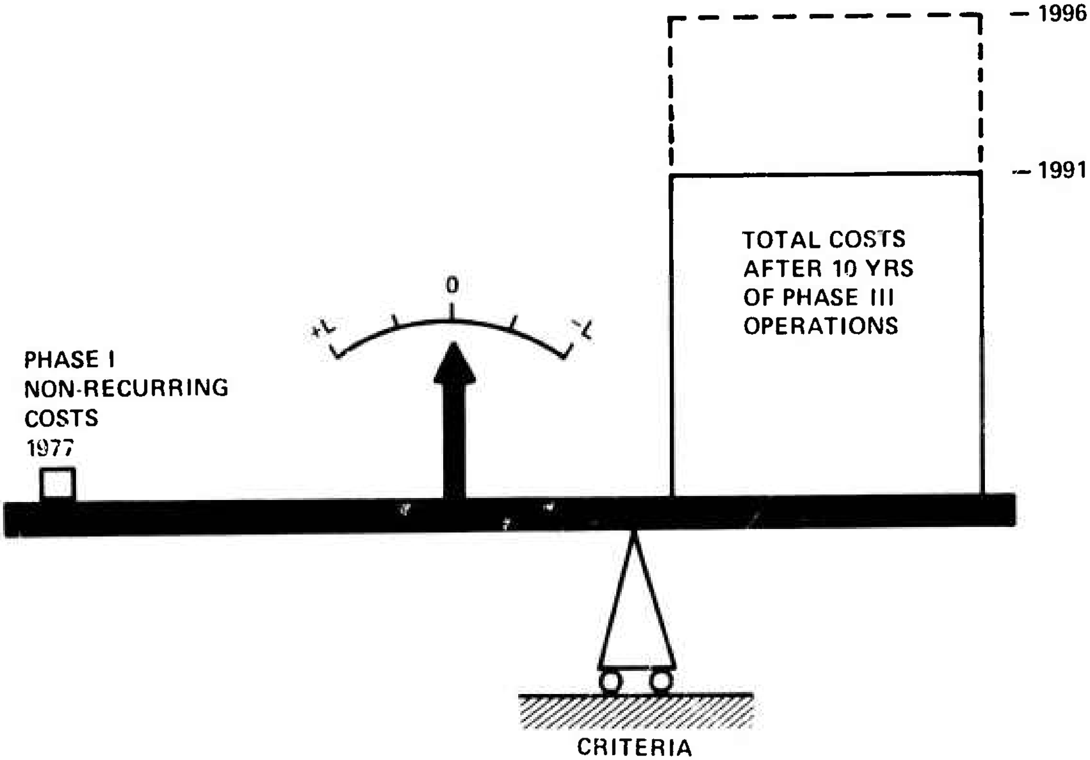


Figure 2-4 Legacy

3.0 Requirements and Assumptions

The system requirements during each of the three phases are shown in Table 3-1. The implementation timing requirements are shown in Figure 3-1.

The assumed Navigation Processing and satellite interface characteristics are listed in Tables 3-2 and -3. The uploadirg of the four phase one satellites is to be accomplished as a single continuous process. The upload message, including both ephemeris data and antenna pointing irformation for all 4 satellites, is forwarded in a block to the US. The messages are then uploaded in a single sequential process into each of the 4 satellites as shoen in Figure 3-2.

The normal satellite station keeping functions are assumed to be accomplished via the SCF's SGLS system and independent of the GPS network stations as shown in Figure 3-3.

TABLE 3-1 Requirements

SUBJECT/PHASE	PHASE I	PHASE II	PHASE III
TEST AREA	WHITE SANDS	A – CONUS (4 SATS) B – WORLD (2 SATS)	WORLD (4 SATS)
BACK-UP EQUIP	NONE	AS NEEDED (AV = 0.7)	100% (AV = 0.99)
UP LOAD	100 k BITS/SAT PRIOR TO TEST PERIOD	100k BITS/SAT A – PRIOR TO TEST PERIOD B – ONCE/DAY	100 k BITS/SAT ONCE/DAY
UPLOAD TIME 1/2/3/4 SATS	20/30/40/50 MINUTES	SAME AS PHASE I	SAME AS PHASE I
MCS/ULS COMM LINE	1 HR/DAY	2 HR/DAY	5 HR/DAY
MONITOR DATA – QUANTITY DATA FORWARDED	800 k BITS/DAY/STN ONCE/HR	1.6 M BITS/DAY/STN ONCE/HR	5 M BITS/DAY/STN ONCE/HR
MCS/NWL COMM LINES	4 HRS EVERY 5 DAYS 1.2 kb/s THRUPUT RATE (NO MCS DATA COMPRESS)	9 HRS EVERY 5 DAYS 1.2 kb/s	24 HRS EVERY 5 DAYS 1.2 kb/s

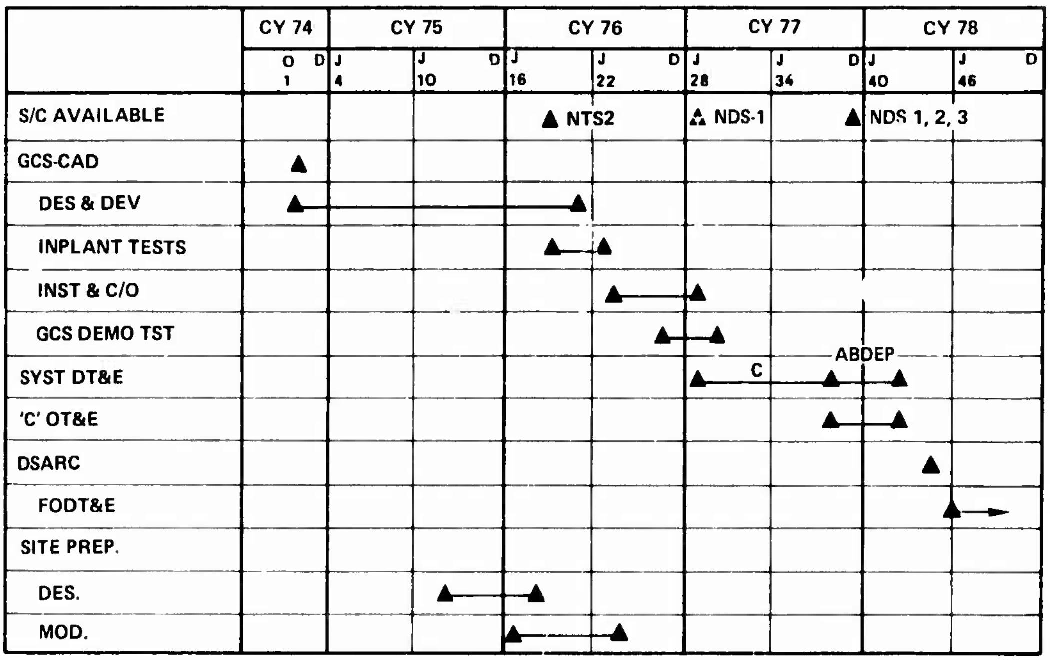


Figure 3-1 Phase I Ground Control Segment

TABLE 3-2 Navigation Processing Assumptions

NAVIGATION PROCESSING

- PROCESSORS LOCATED AT MCS
- ALL CONFIG'S USE NEW 16-BIT CPU, WITH 65K MEMORY
- DISTRIBUTED EPHEMERIS PROCESSING APPROACH
  - SINGLE VEHICLE EPHEMERIS PROC.
  - MULTIVEHICLE CLOCK PROC.
  - PROCESSING TIME

    OBSERVATION PROCESSING 1.4 MIN/SAT - ONCE/HR

    U/L MESSAGE GEN 4 MIN/SAT - ONCE/DAY

REFERENCE EPHEMERIDES PROCESSING (CALIBRATION)

- USE NWL PROCESSORS
- UPLOAD PERFORMED EVERY 5 DAYS

TABLE 3-3 Satellite Interface Assumptions

- SGLS COMPATIBLE TT&C PLUS L-BAND VERIFICATION DATA
- COMMAND RATE 1000 B/S
- SELECTION OF PROTECTED/UNPROTECTED UPLINK
- NAVIGATION DATA LOAD: 100K BITS/DAY/SATELLITE
- TLM BIT RATE: 256 B/S TLM FRAME RATE: 1 FRAME/SEC
- 14 FT S-BAND UPLOAD STATION ANTENNA

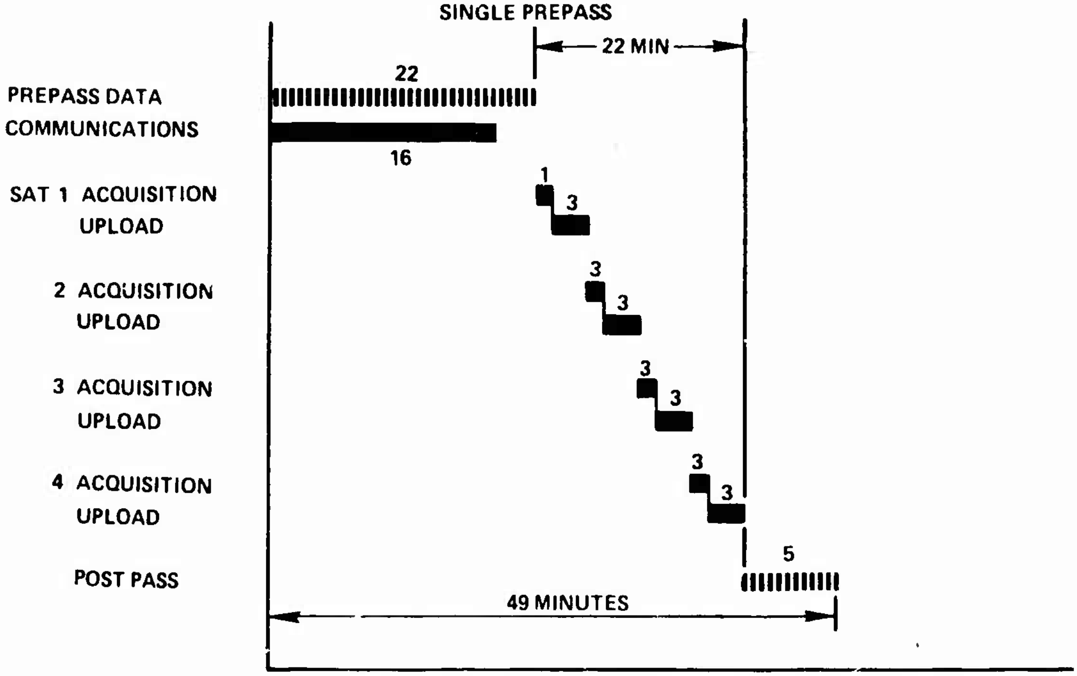


Figure 3-2 Navigation Data Upload Time Line

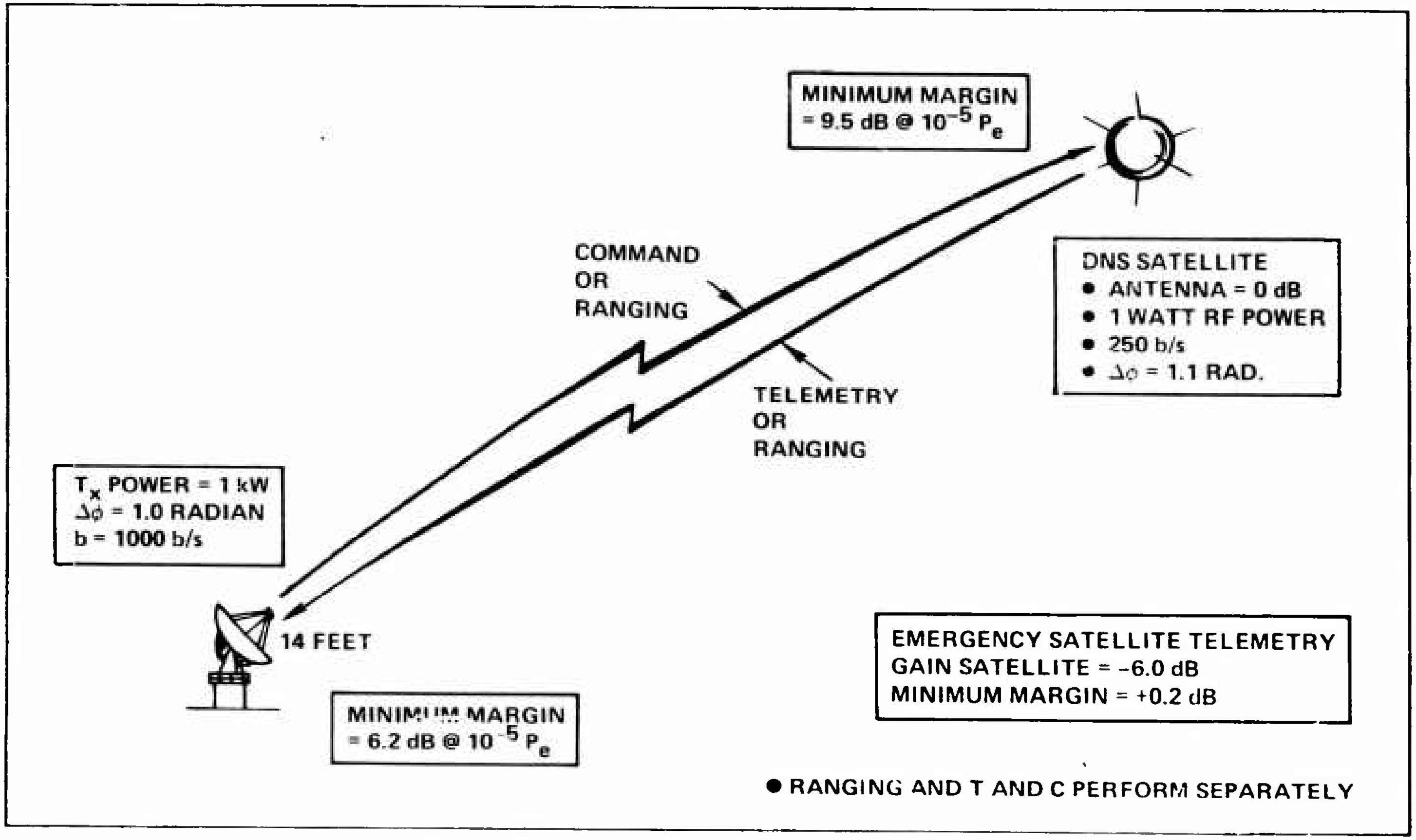


FIGURE 3-3 COMMAND AND TELEMETRY LINK

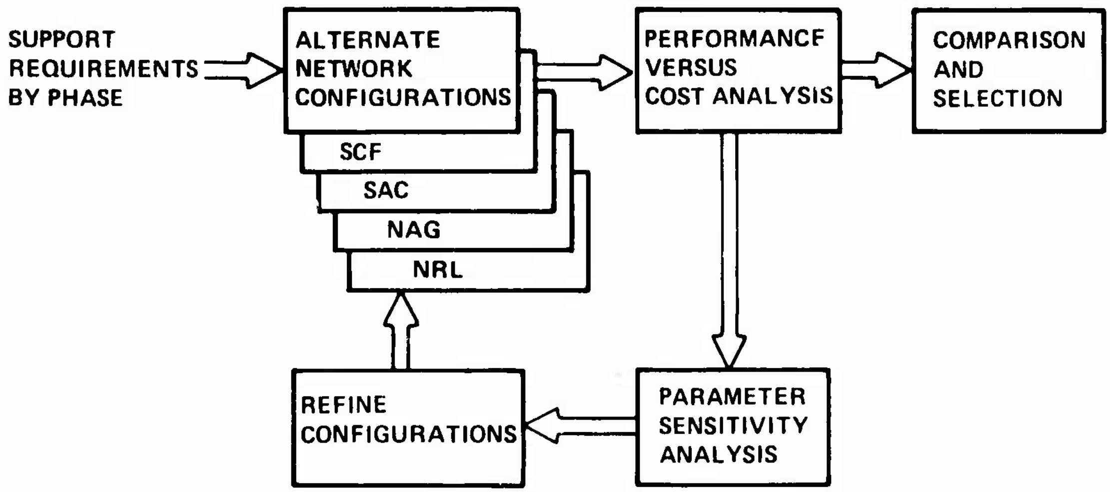


Figure 1.1-1 Control Segment Configuration Selection Approach

4.0 Navigation Upload and Verification

The critical issues affecting the selection of the optimum navigation upload and verification technique are:

- o Cost
- o Satellite Complexity
- o User Time to First Fix
- o User Equipment Complexity
- o Upload Time

The alternatives basically revolve around:

<u>Verification</u>

- o S-Band Downlink
- o L-Band Downlink

<u>Security</u>

- o SCF Secure Word
- o Incremented SCF Secure Word
- o GPS Secure Word
- o GPS Encyphered Upload

a. <u>Cost</u>

The SV must necessarily carry both the S-band and L-band transmission equipments. The impact of the selection will have a negligible cost effect on the SV.

The current baseline US is at the SCF VTS location. The US is independent of VTS equipments and utilizes the facility only. The incorporation of S-band receive capability would involve the installation of a duplexer, paramp and receiver.

b. Satellite Complexity

Since the backup for the US is the SCF, the SV must provide the verification status on the S-band link.

The addition of the status to the L-band link does not increase the SV complexity significantly.

c. Time to First Fix

The largest single element in the user's time to first fix is expected to be the time spent waiting for data. In fact, everything except the C-code acquisition can be done under the data collection task time interval. If, for example, the time to first fix were 40 seconds for a 1200 bit data frame (24 seconds at 50 bps), then each second saved in data collection would represent a 2.5% reduction in time to first fix.

There does not appear to be any compelling reason to repeat the handover word and SID word at six second intervals in the L-band downlink. These repetions of the words add to the time to first fix. In the baseline L-band downlink each 300 bits of data include 56 bits of handover word, 16 bits of SID and 16 bits of telemetry. Each frame therefore contains 7.04 seconds of this type data. This total could be reduced to one handover word and one SID word (1.44 seconds). This would reduce the time to first fix in this example by as much as 14 percent.

It appears that the major reason for breaking up the downlink navigation data is to transmit the telemetry verification.

d. User Equipment Complexity

The user may ignore the telemetry verification data. This can be done with no significant increase in user equipment complexity.

e. Upload Time

The upload time (or throughput) is a function of the upload frame size. In the range of interest, the upload time decreases with decreasing frame size. The frame size is determined by the interval between telemetry verification words.

For S-band verification, the verification interval during the upload function could be as short as 250 ms without interfering with any other function. This would result in upload times of 110 and 130 seconds for BER's of 10^{-5} and 10^{-4} respectively. These high error rates will not be encountered under normal circumstances, but there is a specified requirement for the SV to withstand jamming.

For L-band verification, the verification interval could be 6 seconds (as in the baseline) to 24 seconds. At 6 seconds, the corresponding upload times are 121 and 195 seconds. At 24 seconds, the corresponding upload times are 129 and 860 seconds.

f. Upload and Verification Technique Conclusions

The following major conclusions were reached with respect to the upload verification.

1. S-band verification is superior to L-band from the standpoint of user navigation functions.

2. S-band verification is superior to L-band from the standpoint of control segment upload functions.

The initial analysis involved the tradeoff of L-band versus S-band verification. An overview of the analysis and Philco-Ford's initial S-band verificat verification concept are presented in Section 4.1.

The first iteration results were presented January 8, 1974 and are summarized in Section 4.2. Analysis for this iteration was primarily concerned with error control and security.

The second iteration results were presented January 30, 1974 and are summarized in Section 4.3.

The final upload baseline is described in the SV/Control Segment Interface Control Drawing, HZ-237301.

The upload criteria and their impact on station manning and schedule requirements is presented in Section 4.4.

4.1 Initial GPS Upload Concepts

This section describes the initial Philco-Ford analysis of several concepts for clear mode satellite injection using a SGLS S-band uplink.

The uplink data rate is 1 kbps. The data is assumed to be formatted in 800 bit frames.

The assumed L-band downlink data rate was 40 bps at the time of analysis. The downlink data is assumed to be formatted bit frames with 24 bits available for injection status information.

The ground transmitting station will receive one L-band status word each 20 seconds.

Interspersing injection status with the navigation data was not considered because it would impose bit manipulation requirements on the user segment and no such requirement now exists.

In some cases injection frame identity must be maintained because the order of receipt of data is not constrained. When this is the case, the uncorrectable error rate for the ID field must be less than 10^{-15}. This is true because the satellite must know which frame to request from the ground station when an error is detected.

It is expected that 20 parity bits will allow correction of up to 4 errors in 10 data bits in the uplink frame ($P_u \approx 10^{-16}$ at BER = 10^{-4}).

Frame ID error detection will require only about 10 parity bits to detect 4 errors in 10 data bits in the uplink frame.

a. Injection Logic Concepts:

1. Idle-RQ. - For this logic, a block of frames is transmitted to the satellite. The ground station stops transmitting and waits for the status word to determine whether to retransmit the block or proceed to the next block.

The throughput for this logic is approximately

$$R_I \approx \frac{n}{n+t} (1 - P_B)$$

where n is the number of bits in the block

t is the number of idle (uplink) bit times between the transmission of the last bit of a block and receipt of the last bit of a status word

P_B is the probability that a block will contain any error

NOTE: This definition of throughput does not consider the fact that a fraction of the transmitted bits are overhead.

For this basic system the uplink data blocks would be synchronized with the status word period (n+t) of 20 seconds. Assumming a propagation delay of 150 ms, a processing delay of 100 ms, and a status word transmission time (for 24 bits) of 600 ms, each block would be 24 frames. The probability of error in 24 frames (BER = 10^{-5}) is approximately

$$P_B \approx 0.2 - (0.2)^2/2 + (0.2)^3/6 - (.02)^4/24$$

$$\approx 0.18$$

so

$$R \approx \frac{24}{25} (1 - 0.18) = 0.78$$

Since six 24 frame blocks have to be transmitted, the expected injection time for BER = 10^{-5} is approximately

(6) (20 sec) / 0.78 = 154 seconds

For a noisy link, say BER = 10^{-4},

$$P_B \approx 0.84$$

$$R \approx 0.15$$

and the expected injection time for BER = 10^{-4} is approximately

(6) (20 sec) / 0.15 = 800 seconds

The injection time is extremely sensitive to noise (BER) on the uplink.

2. Simple - RQ. - For this logic, the ground station transmits frames continuously. The satellite error checks each frame and maintains a list of frames received in error. This list is transmitted to the ground station, and the erroneous frames are retransmitted.

This logic is ultimately limited by the downlink throughput (24 bits or two frame numbers per 20 seconds).

The probability of a single frame being in error (at BER = 10^{-5}) is approximately P_F = 0.008. The expected number of retransmissions is 1, and the nominal throughput is $R \approx (1 - P_F)$. This figure must be adjusted to take into account the fact that the erroneous frame may occur near the end of the injection sequence, and the fact that a final frame list must be received before contact with the satellite is terminated.

Let us assume that the erroneous frame list queue starts at frame 12, (the expected time to first error), and the queue is never empty. The ground station will transmit 136 new frames and 12 retransmitted frames.

120 seconds are required to transmit the first list starting on the average 12 frames plus 10 seconds after receipt of the first uplink frame. One of the twelve retransmitted frames should be in error. 20 seconds will be required to determine which. An additional 20 seconds will be required to get the final empty list.

The throughput for BER = 10^{-4} is approximately

$$R_S = \frac{108.800}{(12)\ (0.8) + 10 + 120 + 20 + 20} = \frac{108.8}{179.6} = 0.606$$

3. RQ - Restart. - For this logic, the ground station transmits frames continuously. The satellite error checks each frame and stops loading on error detection. The number of the frame in error is transmitted to the ground. Upon receipt of the reject status and frame number, the ground station retransmits the remainder of the entire load starting at the erroneous frame.

For BER = 10^{-5}, one frame error is expected. The time delay for the reject status slot on the downlink will be on the average 10 seconds. The time delay for the final status slot on the downlink will be on the average 10 seconds. Typically, the ground station will transmit half the upload, then restart (upon receipt of reject status) to transmit the second half. The throughput would be approximately

$$R_R \approx \frac{108800}{108800 + 20000} = 0.845$$

For BER = 10^{-4}, 12 frame errors are expected. We would therefore expect 12 restarts. So the throughput would be approximately

$$R_R = \frac{108.8}{108.8 + 12(10) + 10} = 0.455$$

4. Philco Baseline. - The Philco baseline logic is a variation of Dual-RQ logic in which one of the links (the downlink status) uses error correction instead of error detection. Therefore, no RQ's are sent to the satellite. The baseline uses the S-band telemetry downlink with status words at 250 ms intervals. The logic is essentially the same as 3 above except the restart occurs one frame following any erroneous frame, and only two frames are retransmitted per detected error.

For BER = 10^{-5} (one retransmission), the nominal throughput is approximately

$$R_B = \frac{108800}{108800 + 2(800) + t} = 0.98$$

where t is the time required to get the final status or 500 bit times.

For BER = 10^{-4} (12 retransmissions), the nominal throughput is approximately

$$R_B = \frac{108800}{10880 + 24(800) + t} = 0.85$$

b. Major Problems for L-Band Downlink

1. The L-band Idle-RQ logic performance deteriorates rapidly with increasing BER.

2. The error control requirements for the L-band Simple-RQ and Restart logics will make it necessary to increase the navigation data frame size. The current navigation frame of 800 bits includes 24 unassigned spares. The injection data would have to be 40 to 64 bits. This would decrease the system efficiency by 5 to 7 percent.

3. The error control requirements for the uplink for Simple-RQ and Restart logics will make it necessary to increase the uplink frame size from 800 to about 864 bits.

4. The loss of temporal relationships between frames will impose an error correction requirement on the satellite for the Simple-RQ and Restart logics.

In Phase I, the satellite is assumed to be in the "clear mode" at the start of the injection sequence. The uplink and downlink are SCF SGLS. The uplink data rate is 1 kbps and the downlink is assumed to be 256 bps. Preliminary estimates indicate that a 2 minute injection time can be met with independent bit error probabilities of 10^{-5} for the up and down links.

Data will be transmitted to the satellite in 800 bit blocks. The first 72 bits are overhead and control, and the last 728 bits are the data and parity to be broadcast by the satellite for the users. The satellite will store up to 120 navigation data frames and up to 16 reference data frames.

The satellite will queue the navigation data FIFO and will use each frame once. The satellite will store the reference data in a table which will be referenced sequentially on a cyclic basis.

The injection frame format is shown in Figure 4-1. The satellite will check simple parity on fields 2 through 6 and algebraic parity of field 7. The data will be stored in the satellite memory prior to the final parity check. If no errors are detected, the address pointers (and other tables) will be updated. If errors are detected, the address pointers are not updated and the memory area is overwritten by the next frame. That is, the frame is rejected.

The accept/reject (A/R) status is transmitted to the injection station via the telemetry link. The time slots in the telemetry frame for the A/R status word will be at 250 ms intervals. The A/R status word will be an 8-bit 1 bit error correcting code with four states. These will be defined as:

- o Accept (A)
- o Reject, first (R1)
- o Reject, second (R2)
- o No verification (NOV)

The uplink data and downlink telemetry will be transmitted continuously as shown in Figure 4-2. The nominal state of the A/R status word is NOV. When a frame is accepted, the A/R status word is changed to A for the next two telemetry slots.

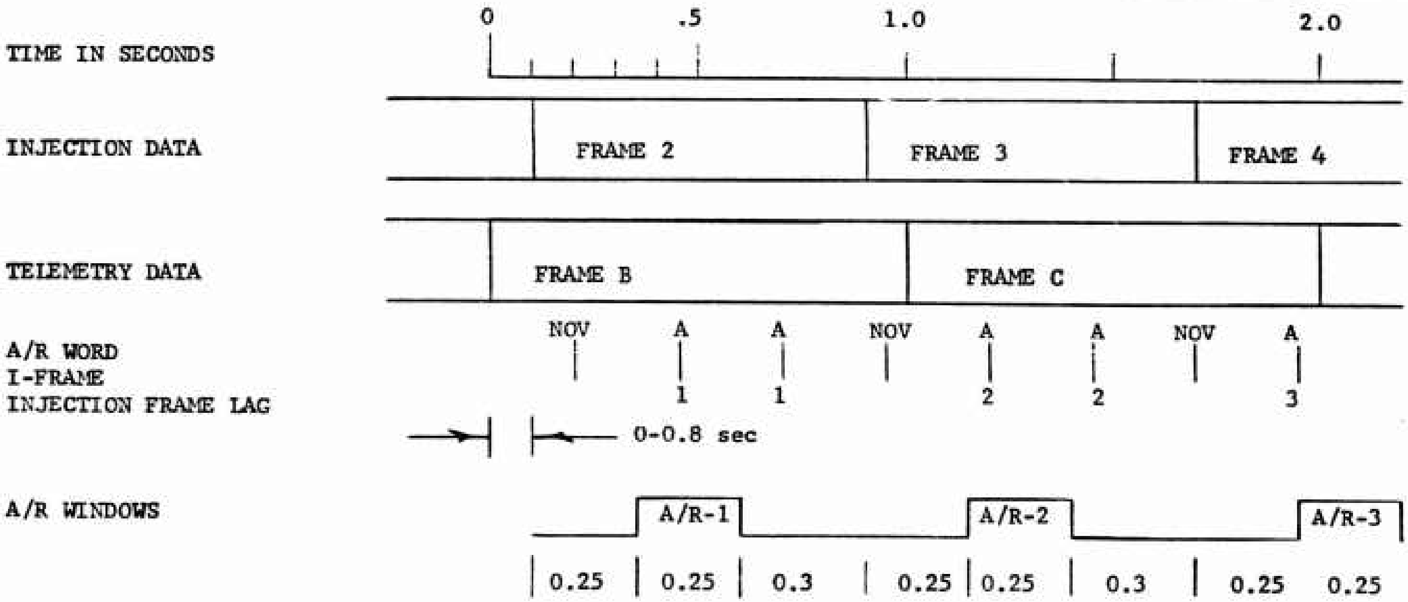
When a parity error is detected, the satellite does the following:

- o Reject the current frame
- o Transmit R1 status
- o Reject the next frame
- o Transmit R2 status

The injection retransmission sequence for a detected error is shown in Figure 4-3. The injection sequence error control is summarized in Figure 4-4.

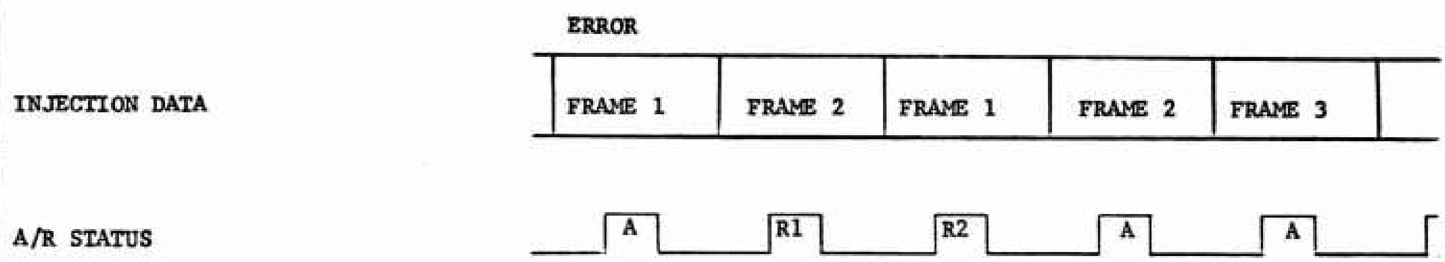
WORD	BITS	DESCRIPTION
1. FS - Frame Sync	32	Identifies start of frame
2. FD - Frame Destination	8	Navigation data queue or reference data table
3. FC - Frame Count	8	Frame count
4. FL - Frame Length	8	Frame length in 16-bit fields - includes parity
5. SID - Satellite ID	8	Includes parity
6. CC - Control Code	8	Provides control and status to satellite - includes parity
7. Data	696	
(o FID-Frame ID	(8)	Data type of this frame)
(o AOD-Age of Data	(8)	Time since data was computed)
(o Downlink Data	(680)	
8. BP - Block Parity	32	Parity for field 7
TOTAL	800	

FIGURE 4-1 INJECTION FRAME FORMAT



NOTES: ACCEPT/REJECT (A/R) WORDS ARE 8 BITS WITH ERROR CORRECTION
TELEMETRY - 256 BPS, 1 FRAME/SEC, 4 A/R WORDS/SEC
A/R DELAY - 150 MS PROPAGATION, 100 MS PROCESSING, 0-250 MS WAIT FOR TLM SLOT

FIGURE 4-2 INJECTION TIMI.NG AT GROUND



NOTE: ON ERROR DETECTION SATELLITE REJECTS CURRENT MESSAGE AND NEXT MESSAGE, AND TRANSMITS R1 STATUS FOR CURRENT MESSAGE AND R2 STATUS FOR NEXT MESSAGE.

FIGURE 4-3 INJECTION RETRANSMISSIONS

4.2 First Iteration. An overview of the GPS Error Control concept and analysis is presented below, along with a summary of the security implementation concepts considered.

4.2.1 Error Control Concept

4.2.1.1 Error Control Criteria. The error control requirements are not, at this time, quantitative. The qualitative constraints are:

a. minimize undetected error rate
b. maximize throughput
c. minimize user equipment complexity
d. minimize satellite equipment complexity

The undetected error rate requirement is assumed to be a maximum of one frame in 10^{15} for injection and navigation data broadcast.

The probability that the user receives good data is equal to the probability that the data was loaded into the satellite without undetected error and was broadcast without undetected error. Using Bayes Rule, this probability is the product of the probability that the data was loaded without undetected error and the probability that the data was broadcast without undetected error.

$$P = (1 - 10^{-15})^2 = 1 - 2 \times 10^{-15}$$

Since the broadcast rate is 30 seconds per frame, the mean time between undetected erroneous frames will be

$$\left(30 \frac{\text{sec}}{\text{frame}}\right) \left(\frac{1}{2 \times 10^{-15}} \frac{\text{frame}}{\text{error}}\right) = 1.5 \times 10^{16} \frac{\text{seconds}}{\text{error}}$$

INJECTION ERROR CONTROL

ERROR	CONTROL	RECOVERY
1. Uplink FS not detected	No Verification on downlink	Ground Station a. Force parity error being transmitted. b. Transmit the missed frame twice (the forced error will cause it to be rejected once). c. Continue the sequence.
2. Detected error in uplink	Simple parity and algebraic parity	Satellite: transmit Reject status for current frame and next frame, and reject both messages.
3. Downlink A/R status	Error correcting code	Detected uncorrectable error treatment is TBD.

FIGURE 4-4 INJECTION ERROR CONTROL

This is about 2×10^8 years per undetected error.

The probability of undetected error for GPS program life of 5 years for 30 satellites is approximately 10^{-6}.

4.2.1.2 <u>Error Control System Consideration</u>. The two links for which error control must be provided are the injection link and the navigation data link.

The injection link is duplex where uplink data known to be in error is retransmitted upon request of the satellite. The navigation data link is simplex where data is retransmitted whether in error or not.

The data on the two links are interrelated. The injection link includes:

- o sync overhead
- o ID and control overhead to be processed by the satellite
- o data to be stored and retransmitted to the user segment
- o error control overhead

The navigation data link includes

- o sync overhead
- o ID and control overhead generated by the satellite
- o data generated on the ground, stored in the satellite, and broadcast
- o error control overhead

a. <u>Protection Requirements</u>

The error control problem from a system standpoint consists of protection of data

- o transmitted from the control segment to the satellite
- o transmitted from the control segment (through the satellite) to the user segment
- o transmitted from the satellite to the user segment

The Control/Satellite data must be error checked prior to processing by the satellite. The Control/User data must be error checked prior to processing by the user.

In addition to the above, the Control/User data should be error checked by the satellite when this data is read out from memory. This implies that some kind of error control coding of the Control/User data should be performed prior to storage of the data on the satellite. This encoder can be eliminated by storing the data as coded by the ground segment.for transmission. The same code can be used for memory diagnostics.

b. Data Content

In many cases some a priori knowledge of the data is available, eg, the range of a variable, the legal character set, the set of legal sequences of characters, etc.

In many cases the processing of data containing undetected errors will result in unreasonable outputs, eg, a surface ship being above the surface, an aircraft being below the surface, etc.

Since these errors are ultimately detected, the undetected error probability for the scheme presented herein is considered conservative.

4.2.1.3 Baseline System Design

The baseline system is shown in Figure 4-5. The Control Segment and Satellite/User links are protected by error detection coding.

a. Injection Logic

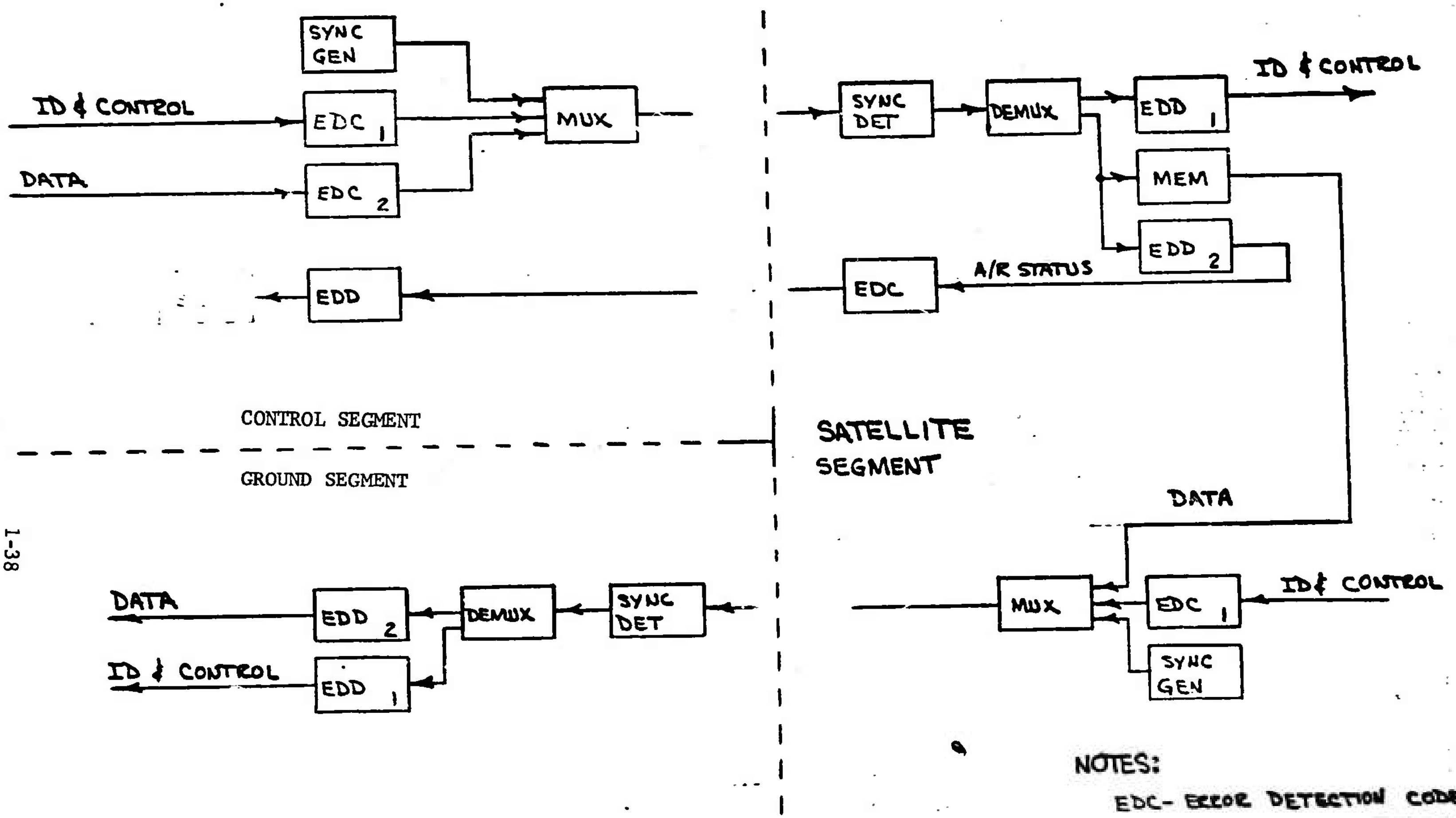
The injection logic is based on the Idle RQ retransmission concept. That is, the control segment will transmit a message then stop and wait for a status word from the L-Band downlink to determine whether to retransmit the current message or proceed to the next message.

b. Error Detection Coding

Error Detection coding for GPS is designed to provide

a. protection against independent bit errors
b. protection against burst errors

In a binary symmetric channel, the absolute random error detection capability of a code is d-1 independent bit errors, where d is the distance between code words.



NOTES:

EDC - ERROR DETECTION CODER

EDD - ERROR DETECTION DECODER

ECC - ERROR CORRECTION CODER

ECD - ERROR CORRECTION DECODER

SC - SEQUENCE CHECK

FIGURE 4-5 GPS SYSTEM ERROR CONTROL CONCEPT

In a high white noise environment where large numbers of random uncorrelated errors are expected, the code distance should be maximized. The Bose-Chaudhuri codes are most efficient for detection of random errors. For detection of burst and multiburst errors, other types of codes (eg, Fire codes) appear to be near optimum.

The desired performance for the GPS can be achieved using any of a multitude of coding schemes.

The algebraic parity scheme has been selected for its known ease of implementation and efficiency.

Models for the GPS transmission channels have not been formulated at this time. It is reasonable to assume that some errors will tend to cluster (due to interference, multipath, etc.) and that the errors to be detected will be bursts and random errors. Further, the injection uplink is not a binary symmetric channel. Half the errors encountered can be detected by the demod, since these will be transformations of 1's to S's or 0's to S's.

The criteria used for selection of a code are

- o absolute protection against any three bit errors in a block
- o statistical undetected error rate of less than 10^{-15} for an equivalent binary symmetric channel

These criteria do not preclude the use of the Bose-Chaudhuri codes of distance greater than 3.

Code Requirements

In order to detect 1, 2, or 3 independent bit errors the form of the code need only meet the following conditions

1. The code has distance greater than 3, or

2a. The code generating polynomial has the form $G(X) = (1 + X) G_1(X)$

b. The length of the code is no greater than the exponent to which $G_1(X)$ belongs.

The polynomial $G_1(X)$ is said to belong to the exponent e if e is the least positive integer such that $G_1(X)$ evenly divides. $X^e + 1$.

EXAMPLE

For block lengths near 1200 bits, the minimum order of G_1 (X) is 11. The minimum number of check bits is 12.

For 12 check bits

$$G_1(X) = 1 + X^9 + X^{11}$$

$$G(X) = 1 + X + X^9 + X^{10} + X^{12}$$

The exponent to which this G_1 (X) belongs is 2047, so the code generated by G_1 (X) will detect 1, 2, or 3 errors absolutly.

Any algebraic code will detect burst errors up to the order of the generator polynomial.and will detect the fraction $1 - 2^{-k}$ of all error patterns (k is the order of the generator polynomial).

The undetected block error rate is therefore

$$P_{uB} = \frac{1 - \sum_{i=o}^{3} \binom{n}{i} p^{i}(1-p)^{n-i}}{2^{k-1}}$$

where

p = BER
k is the order of the generator polynomial
n is the block length.

- Codes Selected

The GPS system will be designed to provide a maximum BER = 10^{-5} for the up and down links. The undetected error requirements are met when the code length is 200 bits maximum and the code is generated by an orde 12 polynomial.

The code selected is TBD, for the blocked data.

The Accept/Reject (A/R) status word will be three bits

A = 101
R = 010

This is a distance 3 code which will detect 2 errors.

c. Injection Errors

Injection errors can occur when

a. an uplink error is undetected or
b. an uplink error is detected and the R status is changed to A status by transmission errors.

The probability of a frame injection error is then

$$P_{uI} = 5 \times P_{uB} + P(R \rightarrow A \mid E)\, P(E) / (5)$$

where P_{uB} is the undetected error probability for a nominal 200 bit code word. And there are 5 such code words (injected data) per broadcast frame. $R \rightarrow A$ is the event R status changed to A.
E is the event detected uplink error in a group of 5632 bits which are equivalent to 5 broadcast frames.

The probability of a detected uplink error P(E) is $(1 - BER)^{5632}$, where each status word covers 5632 bits.

$$1 - P(E) = 1 - 5632 \times 10^{-5} + \frac{(5632)^2}{2} \times 10^{-10} - \frac{(5632)^3}{6} \times 10^{-15}$$

$P(E) = 0.055$

$P(R \rightarrow A \mid E)$ is the probability that all three A/R status bits are in error which is 10^{-15}.

$1/5\ P(R \rightarrow A \mid E)\ P(E) = 10^{-17}$

P_{uB} for $n=200$, $k = 12$, $p = 10^{-15}$ is

$$P_{uB} = 2^{-12} \times \frac{2^4}{24} \times 10^{-12} = 10^{-15}/6$$

$$P_{uI} = 5/6 \times 10^{-15} + 10^{-17} = 0.83 \times 10^{-15}$$

d. Navigation Data Broadcast Errors

Each navigation data frame consists of 6 200 bit fields or 1200 bits.

The probability of undetected error for each field is $P_{uB} = 10^{-15}/6$. So the undetected error for a naviation data frame is 10^{-15}.

4.2.1.4 Implementation Options

Implementation options include

a. Hardware vs. software coding/decoding.
b. Division vs. multiplication coding

These are discussed briefly below.

a. Division vs. Multiplication Coding

Code polynomial can be formed by simply multiplying any message polynomial $M(X)$ by the generating polynomial $G(X)$. In this case the original message will not appear as a sequence in the coded data stream.

For division encoding, the message polynomial is multiplied by X^{n-r} and divided by $G(X)$. The remainder is then the check symbols.

$$X^{n-r} \; M(X) = G(X) \; Q(X) + R(X)$$

where $Q(X)$ is the quotient and $R(X)$ is the remainder. Since addition and subtraction are the same in mod 2 arithmetic, the polynomial

$$V(X) = X^{n-r} \, M(X) + R(X) = Q(X) \; G(X)$$

which is a multiple of $G(X)$ and therefore a code polynomial. The highest order coefficients of $V(X)$ are the same as the coefficients of $M(X)$ which are the message symbols.

Clearly any field of $M(X)$ containing parity information will have the parity for that field preserved.

It seems unlikely, however, that any user will risk using a field in a message known to be in error when good data can be obtained in 30 seconds. So the ability to localize errors using field parity seems to be of little consequence.

When multiplication coding is used and an error is encountered, an error bust will occur in the decoder output from the erroneous bit to the end of the message.

Undetected errors using multiplication coding are likely to generate unreasonable combinations of data and will assist with the error detection process.

b. Hardware vs. Software

This trade-off is dependent upon processor loading, and is deferred.

4.2.2 Security Concepts. Eight Upload/Verification techniques are described and compared on the basis of:

- Load Time
- Spoof Protection
- SCF support requirements
- Satellite Impact
- Control Segment Impact
- Recovery Technique
- Navigation Format/User Impact

4.2.2.1 Upload Protocols. The four upload protocols considered were:

- SCF secure word
- Incrementing SCF secure word
- GPS secure word
- GPS encrypted upload

These protocols are defined in Figures 4-6 and 4-7.

4.2.2.2 Verification Protocols. The two verification protocols considered were:

- SGLS telemetry (S-band)
- L-band

These protocols are defined in Figure 4-8.

4.2.2.3 Upload Error Control. Error control for the two verification protocols is summarized in Figures 4-9 and 4-10.

4.2.2.4 Comparison of Upload/Verification Techniques. Four upload techniques are described below. Each technique may utilize either S-band or L-band verification. This makes a total of eight overall concepts considered.

a. SCF Secure Word. The satellite structure for this technique is shown in Figure 4-11. The message structure is shown in Figure 4-12.

b. Incrementing SCF Secure Word. The satellite structure for this technique is shown in Figure 4-11. The message structure is shown in Figure 4-13.

c. GPS Secure Word. The satellite structure for this technique is shown in Figure 4-14. The message structure is shown in Figure 4-15.

d. Encrypted Upload. The satellite structure for this technique is shown in Figure 4-16. The message structure is shown in Figure 4-17.

The eight concepts are compared as shown in Figure 4-18 and significant conclusions are summarized in Figure 4-19.

UPLOAD PROTOCOLS

A. SCF SECURE WORD

- SECURE WORD LOADED BY SCF ONCE/DAY DURING NORMAL SUPPORT (CYPHERED)
- UNPROTECTED UPLOAD PREAMBLE CONTAINS SECURE WORD
- UNPROTECTED LINK ALWAYS OPEN FOR UPLOAD

B. INCREMENTING SCF SECURE WORD

- INITIAL SECURE WORD LOADED BY SCF (CYPHERED)
- UNPROTECTED UPLOAD BLOCK CONTAINS SECURE WORD
- SECURE WORD INCREMENTS ON EACH BLOCK
- UNPROTECTED LINK ALWAYS OPEN

FIGURE 4-6 UPLOAD PROTOCOLS

UPLOAD PROTOCOLS (CONT'D)

C. GPS SECURE WORD

- GS LOADS SGLS COMPATIBLE UNPROTECTED LINK ENABLE (CYPHERED)
- UNPROTECTED UPLOAD
- GS LOADS SGLS COMPATIBLE UNPROTECTED LINK DISABLE (CYPHERED)

D. GPS ENCYPHERED UPLOAD

- GS LOADS ALL NAV. DATA USING KIR-23 WITH DELAYED AUTHENTICATION

FIGURE 4-7 UPLOAD PROTOCOLS (CONT'D)

CANDIDATE VERIFICATION PROTOCOLS

1. SGLS TLM
   - ACCEPT - REJECT DELAY ~ 1 FRAME ~ 1.0 SEC
   - CAN REDUCE DELAY WITH SUPERCOMMUTATION
   - 1000 BIT UPLOAD FRAME

2. L-BAND REFERENCE
   - ACCEPT - REJECT DELAY ~1 FRAME ~30 SEC
   - SUPERCOMMUTATION WOULD COMPLICATE NAVIGATION DATA FORMAT
   - COMMAND COUNT COULD BE MONITORED SINCE LINK IS PROTECTED

FIGURE 4-8 CANDIDATE VERIFICATION PROTOCOLS

ERROR CONTROL FOR UPLOAD DATA

VERIFICATION CHANNEL	S-BAND TLM	L-BAND NAV DATA
UPLOAD FRAME LENGTH	1000 BITS	30,000 BITS
NUMBER OF FRAMES/UPLOAD	100	3
BLOCK LENGTH FOR ERROR CONTROL	1000	1000
NUMBER OF BLOCKS/UPLOAD	100	100
PARITY CHECK LENGTH	32	32
UNDETECTED ERROR RATE AT $P_B = 10^{-5}$		
PER BLOCK	$\leq 10^{-17}$	$\leq 10^{-17}$
PER UPLOAD	$\leq 10^{-15}$	$\leq 10^{-15}$
5 YR MISSION	$\leq 10^{-10}$	$\leq 10^{-10}$
EXPECTED FRAME REJECTS/UPLOAD	1	1
TIME PENALTY PER REJECT	~2 SEC	~60 SEC

FIGURE 4-9 ERROR CONTROL FOR UPLOAD DATA

SGLS TLM UNPROTECTED LINK AND PROTECTED LINK

- BLOCK SIZE TO MATCH DELAY → 1000 BIT BLOCKS OPTIMUM
- OVERLAP TRANSMIT AND VERIFY ADDS 1 SEC
- 10^{-5} BER → 1 BLOCK ERROR, RETRANSMISSION OF TWO BLOCKS ADDS 2 SEC
- SCF ENCRYPTED UPLOAD → RETRANSMISSION OF AVERAGE OF 3 163 MSEC BLOCKS EACH ERROR BY 3 ERRORS (300,000 BITS) ADDS 1.5 SEC

L-BAND UNPROTECTED LINK

- BLOCK SIZE TO MATCH DELAY → 30,000 BIT BLOCKS OPTIMUM
- OVERLAP TRANSMIT AND VERIFY ADDS 30 SEC
- 10^{-5} BER → 1 BLOCK ERROR, RETRANSMISSION OF TWO BLOCKS ADDS 60 SEC
- SCF ENCRYPTED UPLOAD → RETRANSMISSION OF AVERAGE OF 200 163 MSEC BLOCKS EACH ERROR BY 3 ERRORS (300,000 BITS) ADDS 90 SEC

FIGURE 4-10 SGLS TLM UNPROTECTED LINK AND PROTECTED LINK

SCF SECURE WORD/INCREMENTING SCF SECURE WORD

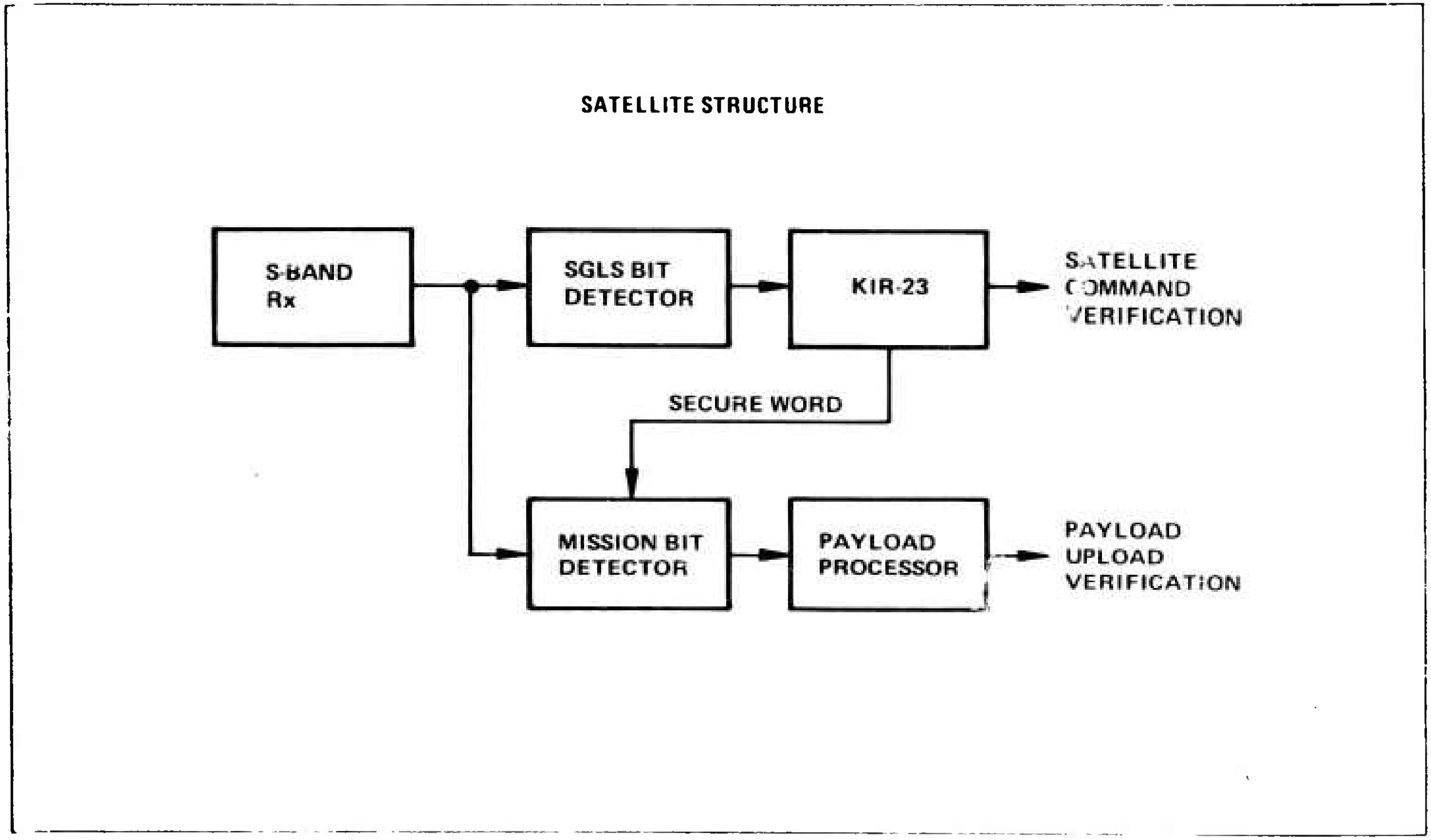


FIGURE 4-11 SCF SECURE WORD/INCREMENTING SCF SECURE WORD

SCF SECURE WORD

UPLOAD MESSAGE STRUCTURE

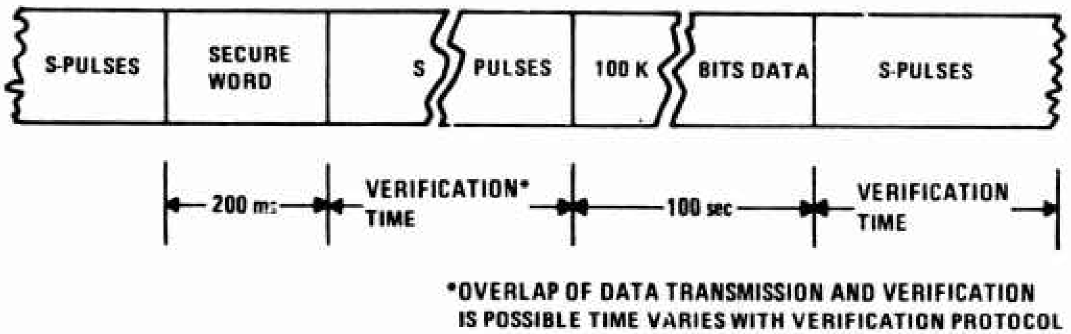


FIGURE 4-12 SCF SECURE WORD

INCREMENTING SCF SECURE WORD

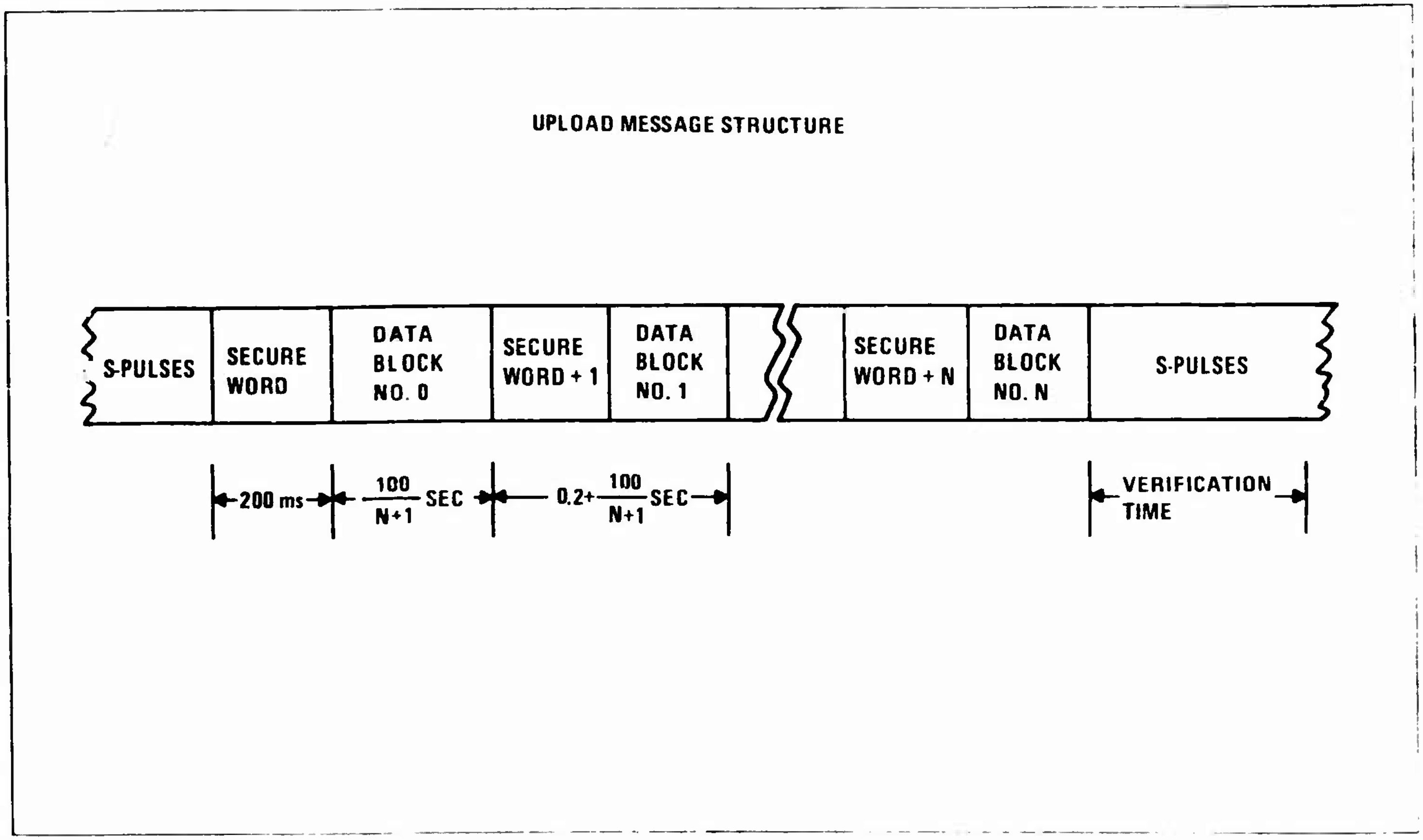


FIGURE 4-13 INCREMENTING SCF SECURE WORD

GPS SECURE WORD

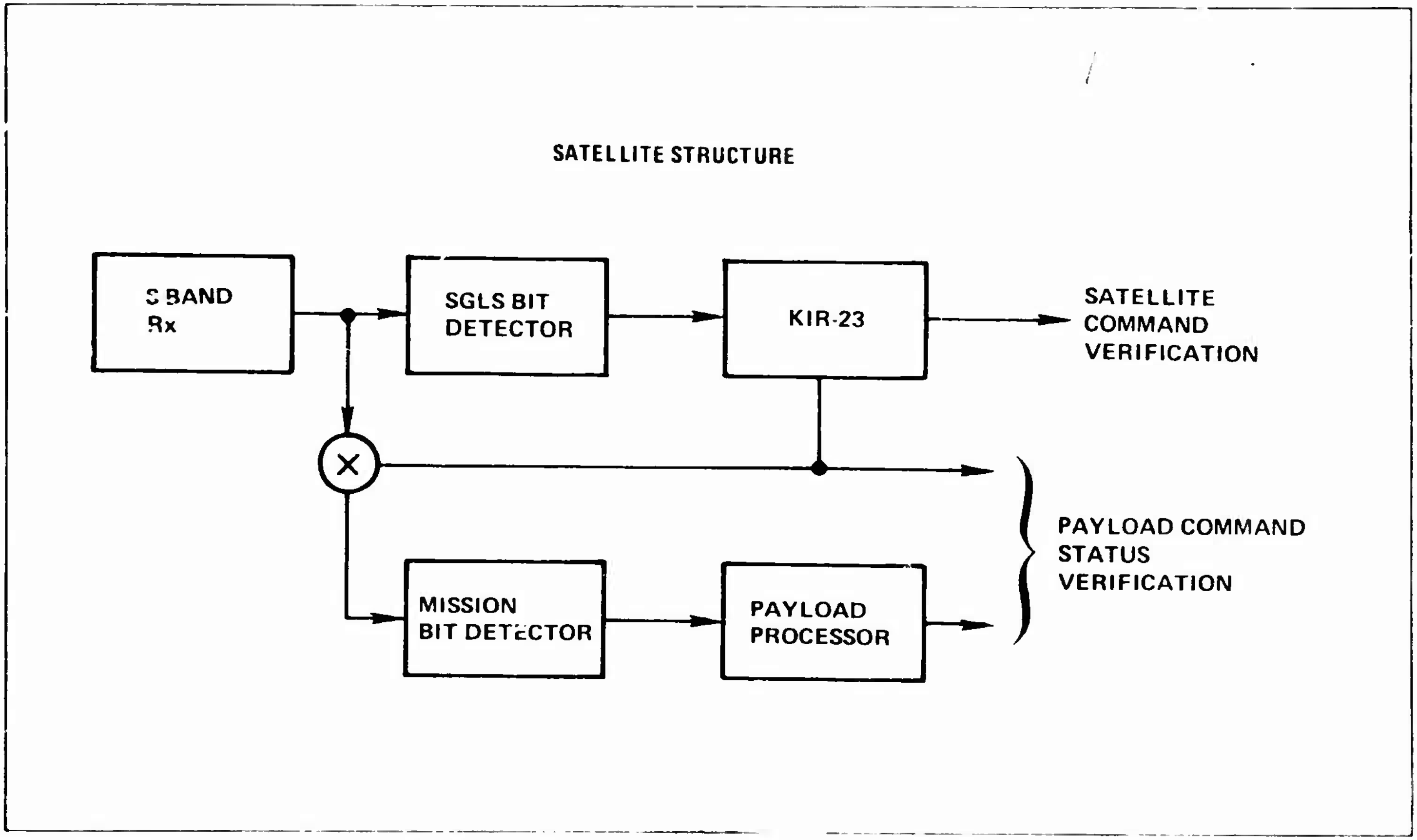


FIGURE 4-14 GPS SECURE WORD

GPS SECURE WORD

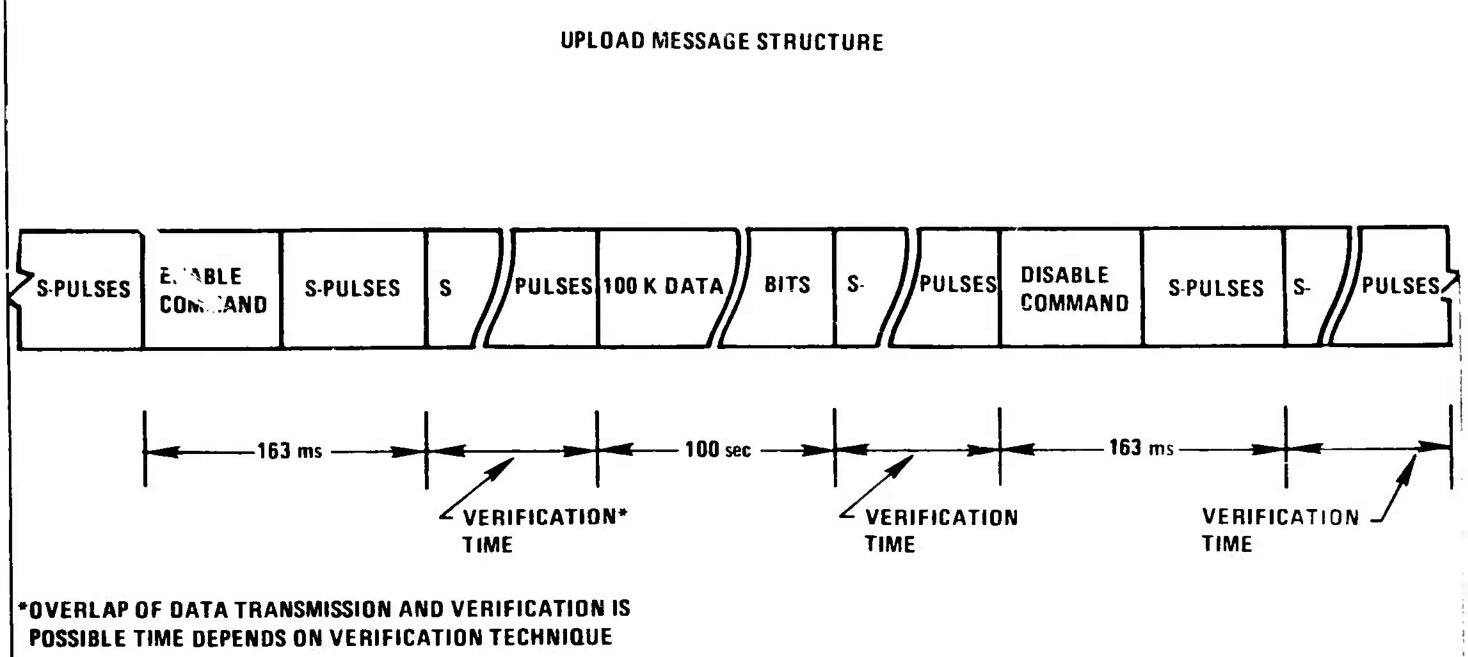


FIGURE 4-15 GPS SECURE WORD

SCF ENCRYPTED UPLOAD

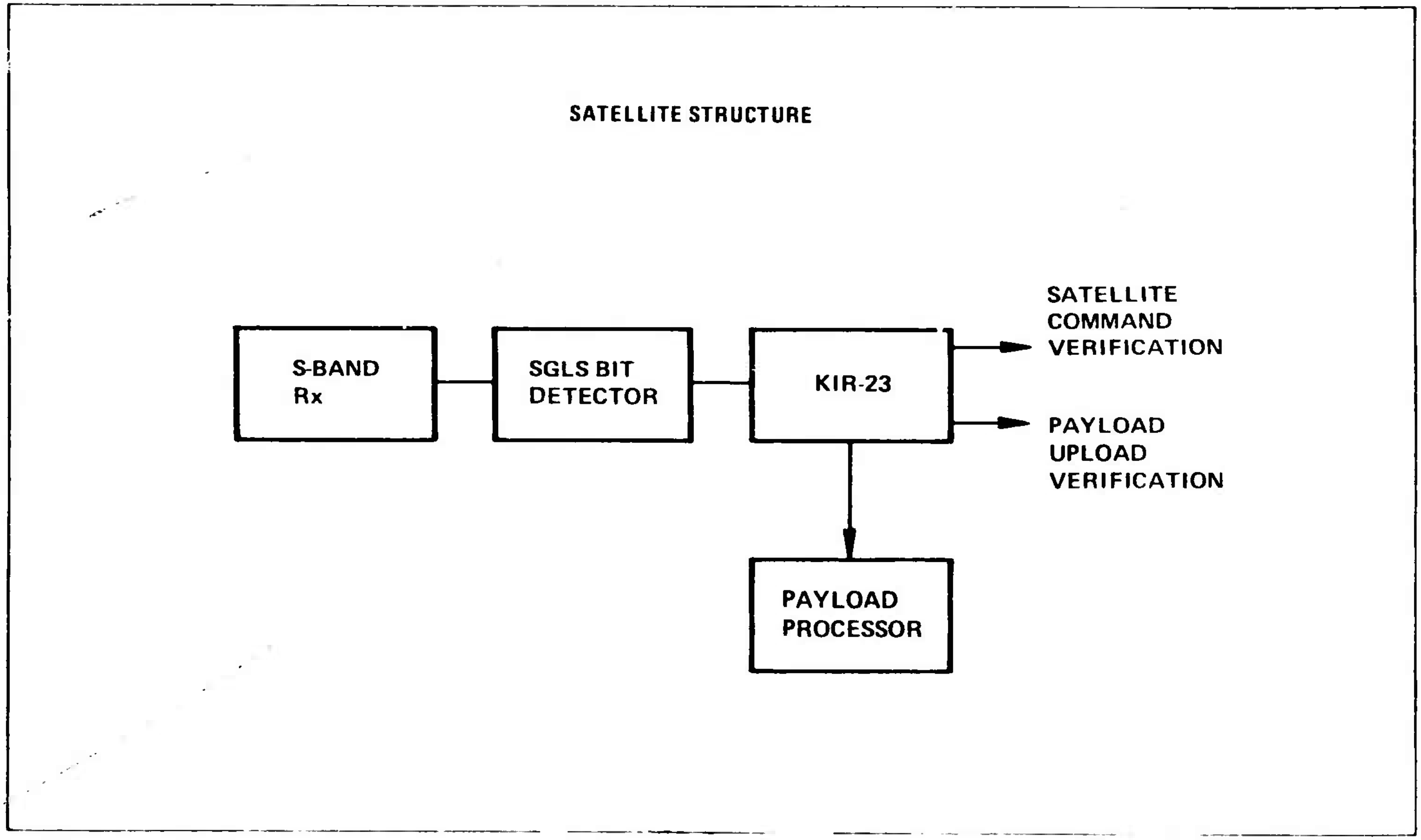


FIGURE 4-16 SCF ENCRYPTED UPLOAD

SCF ENCRYPTED UPLOAD

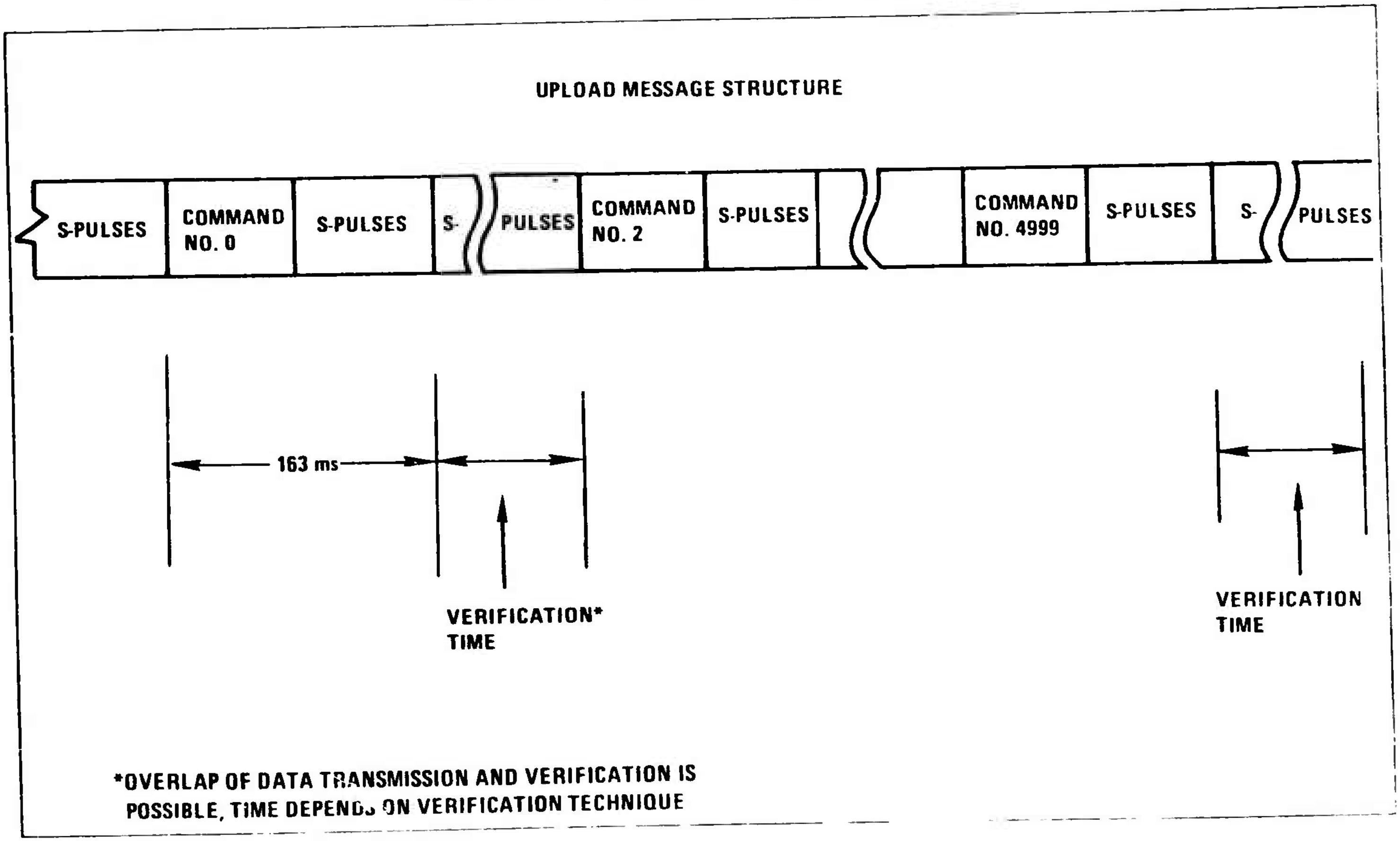


FIGURE 4-17 SCF ENCRYPTED UPLOAD

COMPARISON OF UPLOAD CANDIDATES

UPLOAD PROTOCOL CANDIDATES	SCF SECURE WORD		GPS INCREMENT OF SECURE WORD		GPS SECURE WORD		GPS SECURE LINK	
VERIFICATION PROTOCOL CANDIDATES	SGLS TLM	L-BAND VER	SGLS TLM	L-BAND VER	SGLS TLM	L-BAND VER	SGLS TLM	L-BAND VER
LOAD TIME*, min	1.7	3.2	2.1	3.2	1.7	3.6	13.6	15.5
SPOOF PROTECTION	HRS	HRS	WEEKS	WEEKS	EXCEPT DURING LOAD	EXCEPT DURING LOAD	SECURE	SECURE
SCF SUPPORT	1/DAY	1/DAY	1/WEEK	1/WEEK	NONE	NONE	NONE	NONE
SATELLITE IMPACT	MORE	MOST	MORE	MOST	LESS	MORE	LEAST	LESS
CONTROL SEG IMPACT	MINIMUM		SMALL		KI-23 AT MCS		KI-23 AT ULS	
RECOVERY	GET NEW SCF WORD		GET NEW SCF WORD		FILL CMD		VCC OR FILL COMMAND	
NAV FORMAT/USER IMPACT	NO	YES	NO	YES	NO	YES	NO	YES

*UPLINK BER 10^{-5}

FIGURE 4-18 COMPARISON OF UPLOAD CANDIDATES

SUMMARY OF UPLOAD TECHNIQUES

- VERIFICATION OF UPLOAD VIA L-BAND INCREASES LOAD TIME BY APPROXIMATELY 50% - NOT A SERIOUS IMPACT ON TIME-LINES.
- USE OF SCF FOR PROVIDING SECURE WORD WOULD REQUIRE AS MUCH SCF SUPPORT AS IF SCF PROVIDED ENTIRE UPLOAD. ONLY ADVANTAGE IS REDUCTION IN SCF SCHEDULING CONSTRAINTS.
- POSSIBLE PHASE III REQUIREMENT FOR FULLY SECURE UPLOAD WILL HAVE SIGNIFICANT IMPACT ON UPLOAD TIME-LINE AND UPLOAD STATION SCHEDULING.

FIGURE 4-19 SUMMARY OF UPLOAD TECHNIQUES

4.3 Second Iteration

The next iteration examined in greater detail the following two upload security techniques:

- o Incrementing SCF Secure Word
- o GPS Secure Word

Error Control, Message Format and Timing relationships are addressed. Load verification at the MCS versus the US is considered and the "Bent Pipe" concept depicted. The section concludes with a list of advantages of using S-band for verification and a description of the Philco-Ford recomended approach. During Phase I this involves:

- o US with S-band Receive and INY at ELM
- o Adding INY to KTS for backup upload via the SCF

4.3.1 Security Techniques. The two security concepts considered on this iteration are summarized in Figure 4-20.

4.3.2 Upload/Verification Concept. The concept resulting from this iteration is summarized in Figures .4-21 through 4-24.

Figure C-1.4-25 contains a comparison of the L-band verification concept to an equivalent S-band verification concept. The potential benefits of the utilization of S-band verification are shown in Figure .4-26.

4.3.3 MCS vs US Verification. The consideration of MCS and US verification is summarized in Figure 4-27. The MCS verification concept (Bent Pipe) is depicted in Figure 4-28.

4.3.4 Philco Recommendation. Philco-Ford recommendations for Phase I, II and III are shown in Figures 4-29 and 4-30.

UPLOAD PROTOCOLS

INCREMENTING SCF SECURE WORD

- SECURE WORD LIST LOADED BY SCF (CYPHERED), SENT TO MCS
- UNPROTECTED UPLOAD BLOCK CONTAINS SECURE WORD
- SECURE WORD INCREMENTS ON EACH BLOCK
- UNPROTECTED LINK ALWAYS OPEN
- 20-BIT WORD GIVES ONE DAY PROTECTION
- MCS-TO-ULS COMM LINK MAY REQUIRE SECURITY
- NO INY REQUIRED AT MCS OR ULS

GPS SECURE WORD

- GPS LOADS SGLS COMPATIBLE UNPROTECTED LINK ENABLE (CYPHERED)
- UNPROTECTED UPLOAD
- GPS LOADS SGLS COMPATIBLE UNPROTECTED LINK DISABLE (CYPHERED)
- REQUIRES INY AT MCS OR ULS
- ELIMINATES GPS/SCF CRYPTO INTERFACE
- REQUIRES S-BAND TLM RECEIVER AT ULS

FIGURE 4-20 UPLOAD PROTOCOLS

INJECTION TIMING

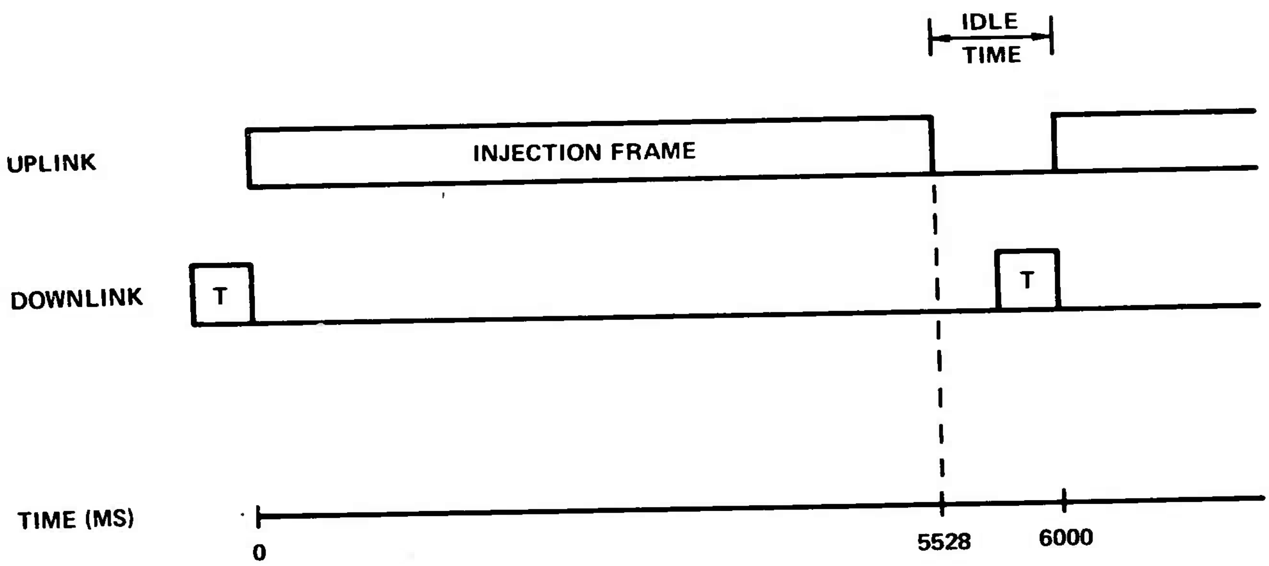


FIGURE 4-21 INJECTION TIMING

INJECTION FRAME (18 BLOCKS)

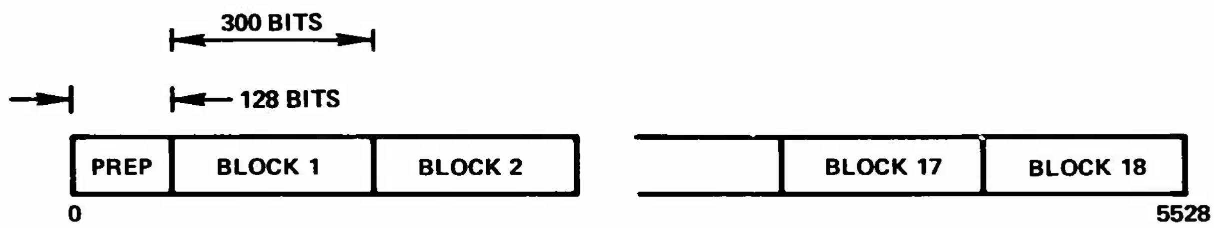


FIGURE 4-22 INJECTION FRAME (18 BLOCKS)

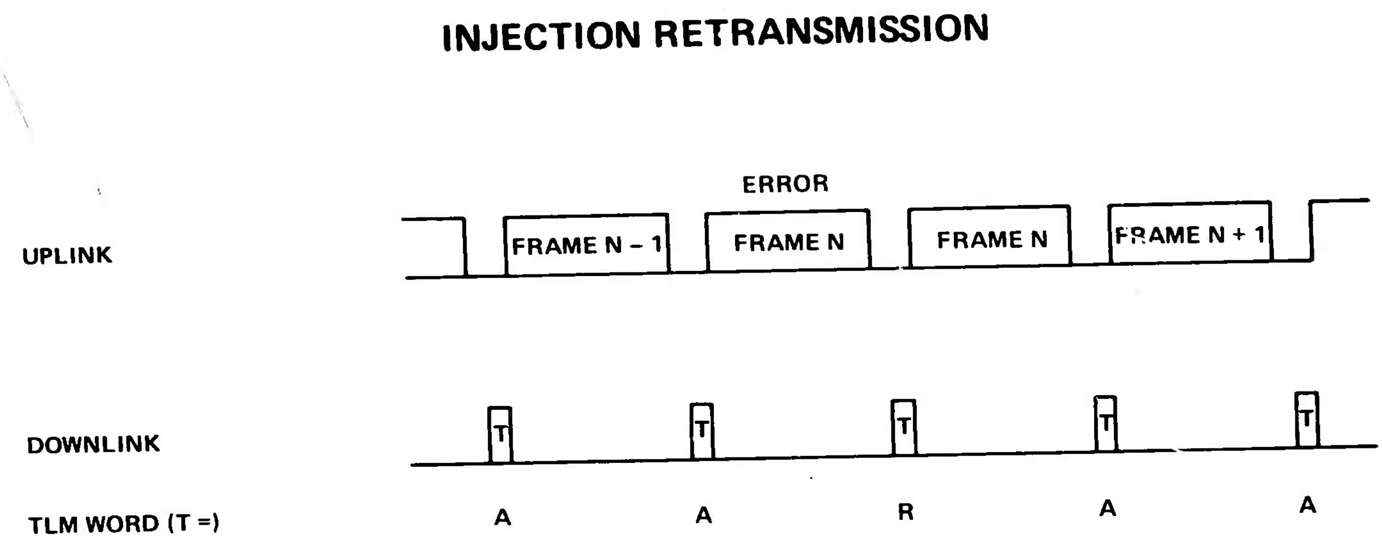


FIGURE 4-23 INJECTION RETRANSMISSION

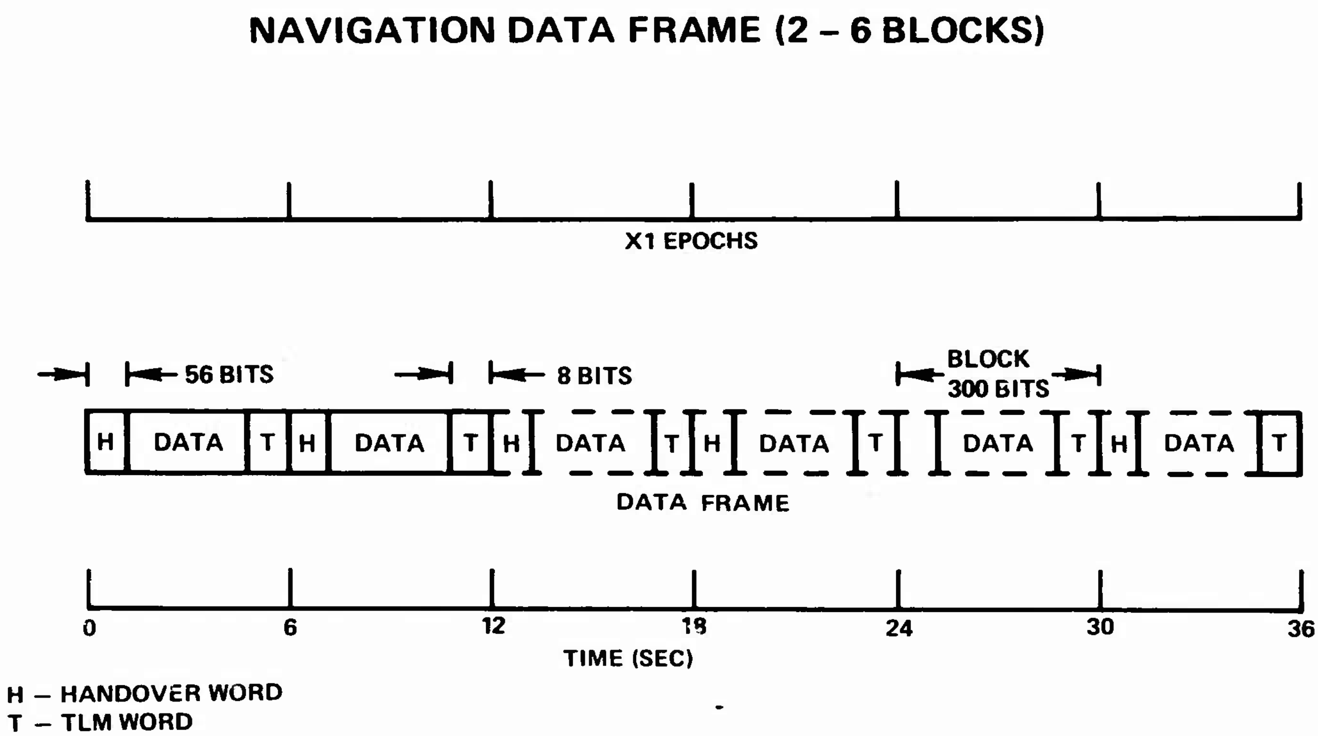


FIGURE 4-24 NAVIGATION DATA FRAME (2 - 6 BLOCKS)

ERROR CONTROL FOR UPLINK DATA

VERIFICATION CHANNEL	S-BAND TLM	L-BAND NAV DATA
UPLOAD FRAME LENGTH	900 BITS	5528 BITS
NUMBER OF FRAMES/UPLOAD	114	19
BLOCK LENGTH FOR ERROR CONTROL	300	300
NUMBER OF BLOCKS/UPLOAD	342	342
PARITY CHECK LENGTH	16	16
UNDETECTED ERROR RATE AT $P_B = 10^{-5}$		
PER BLOCK	10^{-16}	10^{-16}
PER UPLOAD	$3X10^{-14}$	$3X10^{-14}$
5 YR MISSION	$5X10^{-11}$	$5X10^{-11}$
EXPECTED FRAME REJECTS/UPLOAD	1	1
TIME PENALTY PER REJECT	~2 SEC	~6 SEC
EXPECTED LOAD TIME	1.9 MIN	2.0 MIN

FIGURE 4-25 ERROR CONTROL FOR UPLINK DATA

BENEFITS OF DEDICATED S-BAND TELEMETRY

ADVANTAGES

- BETTER NAV PAYLOAD SECURITY
- SIMPLER SCF/GPS INTERFACES
- AUTONOMOUS RECOVERY PROCEDURES
- DIRECT ACCESS TO SATELLITE TELEMETRY
- CAN PROVIDE NORMAL T&C SUPPORT
- MINIMUM SCF SUPPORT REQUIREMENTS
- USES EXISTING CMD FORMATS AND TECHNIQUES
- SIMPLIFIES SATELLITE DESIGN
- SIMPLIFIES NAVIGATION DATA FORMAT

DISADVANTAGES

- HIGHER INITIAL UPLOAD STATION COST

FIGURE 4-26 BENEFITS OF DEDICATED S-BAND TELEMETRY

LOAD VERIFICATION AT MCS VERSUS ULS

OPTIONS

- OPERATIONS CONTROL AT MCS OR ULS
- COMMAND SOFTWARE AT MCS OR ULS
- INY AT MCS, ULS, OR SCF

CONSIDERATIONS

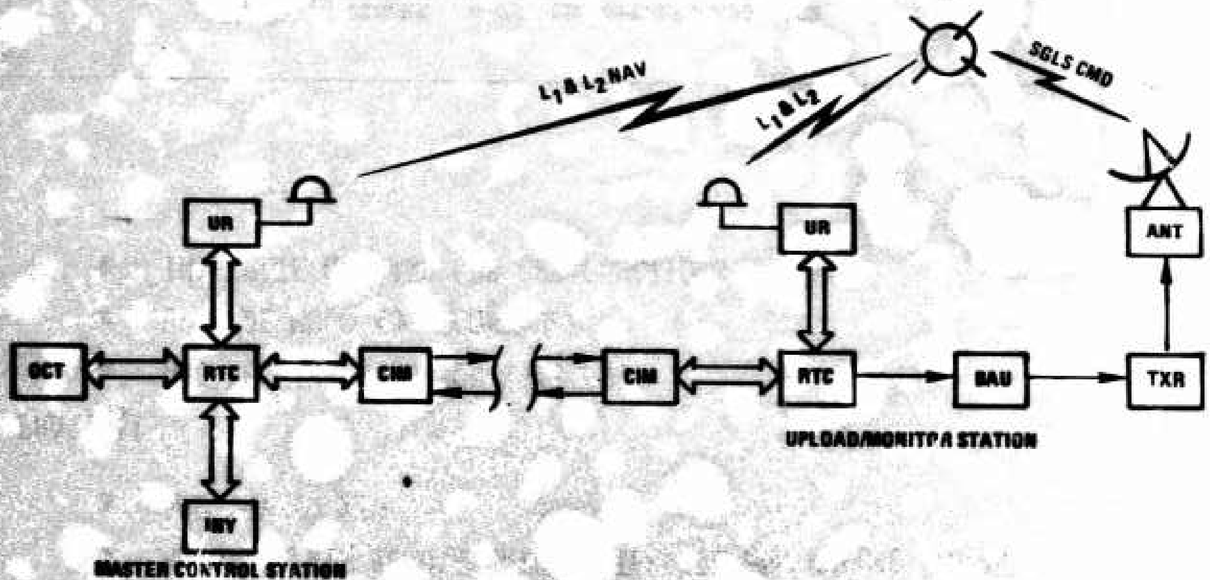
- CENTRALIZED OPERATION CONTROL MINIMIZES MANNING
- IF COMMAND SOFTWARE IS AT MCS, BACK-UP MUST BE PROVIDED AT ULS
- IF INY AT MCS, MCS/ULS COMM LINK MUST BE SECURE

PREFERRED APPROACH

- REAL-TIME OPERATIONS CONTROL FROM MCS
- COMMAND SOFTWARE AND INY AT ULS

FIGURE 4-27 LOAD VERIFICATION AT MCS VERSUS ULS

BENT PIPE CONCEPT



KEY:

- OCT - OPERATOR CONTROL TERMINAL
- RTC - REAL-TIME CONTROLLER
- UR - USER RECEIVER
- CIM - COMMUNICATIONS INTERFACE AND MODEM
- BAU - BASEBAND ASSEMBLY UNIT (SGLS)
- TXR - TRANSMITTER-EXCITER
- ULS - UPLOAD STATION

FEATURES

- ULS TRANSPARENCY
- REAL-TIME OR STORE & FORWARD
- LOAD VERIFICATION VIA L-BAND
- ERROR CONTROL BY RETRANSMISSION
- REDUNDANT VERIFICATION MONITORING
- NO KG AT REMOTE SITES
- ALL COMMAND SOFTWARE AT MCS

FIGURE 4-28 BENT PIPE CONCEPT

RECOMMENDED APPROACH

PHASE I

- MCS AT MUGU
- MONITORS AT MUGU, HAU, MA, ELM
- ULS WITH S-BAND RECEIVE AND INY AT ELM
- MUGU/STC/KTS REMOTE BATCH INTERFACE FOR UPLOAD BACKUP
- ADD INY TO KTS

PHASE II

- ADD RECEIVERS TO MON STATIONS
- UPGRADE MUGU TO SECOND ULS
- INTEGRATE NAG AND GPS OPS FUNCTIONS

FIGURE 4-29 RECOMMENDED APPROACH

RECOMMENDED APPROACH (CONT)

PHASE III

- UPGRADE MAINE TO BACKUP ULS
- ASSUME T&C RESPONSIBILITY FROM SCF
- ADD REDUNDANCY TO ALL MONITOR STATIONS AND MCS
- UPGRADE NAG SUPPORT COMPUTER CENTER AND MOVE NML FUNCTIONS TO MUGU

FIGURE 4-30 RECOMMENDED APPROACH (CONT)

4.4 Upload Impact on Manpower Requirements. The following material addresses the impact of various upload criteria on manpower and facility requirements and was presented at the January 8, 1974 meeting.

An upload station (US) which is shared would minimize the number of short upload periods in order to require the least amount of facility time during Phases IIB and III. On the other hand, a dedicated US would be scheduled in order to minimize manpower costs. Thus, all uploading would be scheduled to occur during a single 8 hour shift, if possible. These criteria are summarized in Figure 4-31.

During Phase I and IIA, both types of facilities would be scheduled in a way which would upload the satellites as close as possible to the start of the test period.

Figures 4-32 through 4-45 show the schedules which this would impose on the following possible US's: KOD/ELM, MUG, SPO, MIN, and VIR.

Figure 4-46 shows the major conclusions reached as a result of this analysis.

UPLOAD CRITERIA

	PHASE IIA	PHASES IIB & III
SHARED FACILITY	UPLOAD ALL SATELLITES AS CLOSE AS POSSIBLE TO START OF TEST PERIOD	MINIMUM NUMBER OF SHORT UPLOAD PERIODS
DEDICATED FACILITY		UPLOAD DURING ONE SHIFT, OR WITH MINIMUM OVERTIME

FIGURE 4-31 UPLOAD CRITERIA

PHASE I SATELLITE VIEW TIMES AT UPLOAD STATION

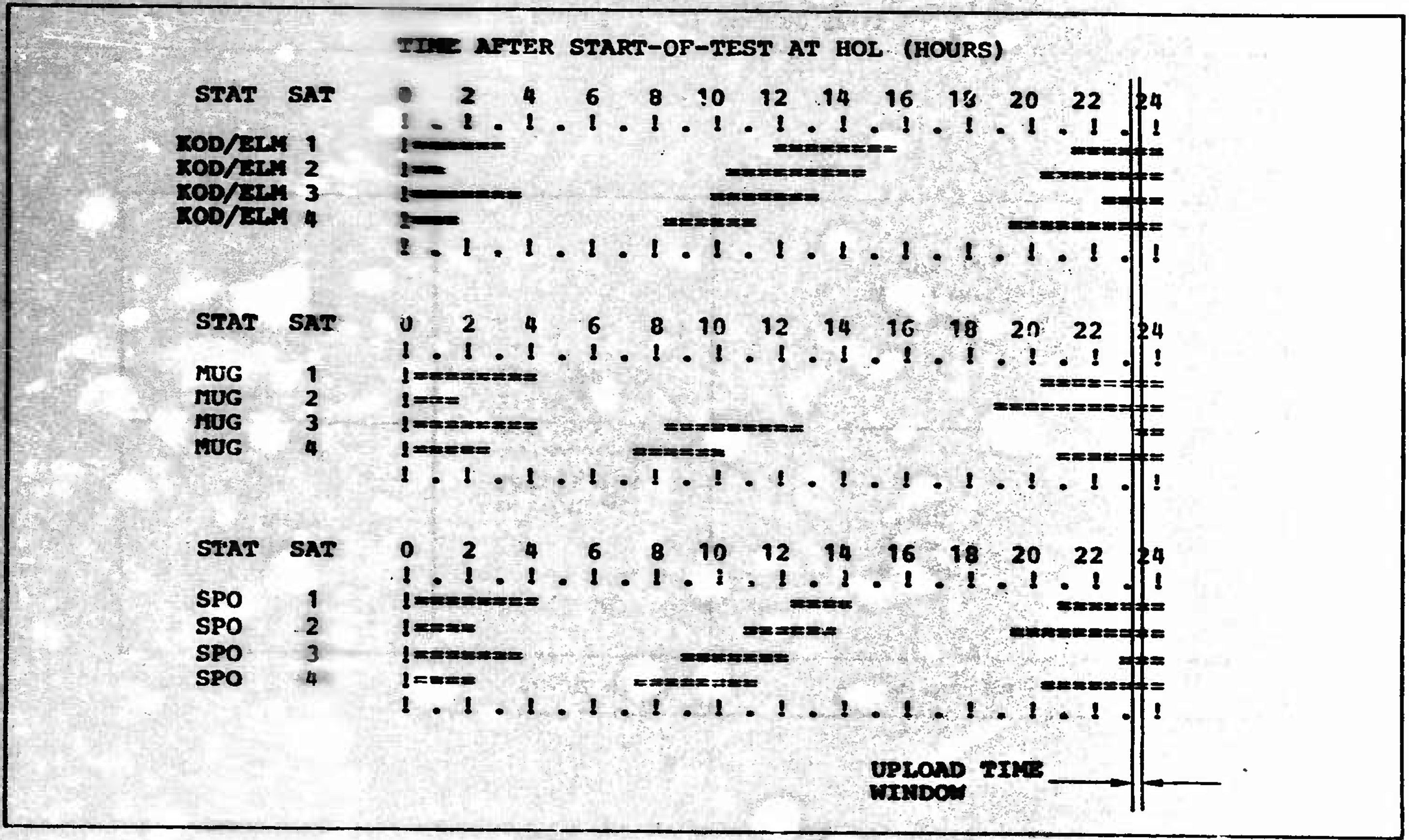


FIGURE 4-32 PHASE I SATELLITE VIEW TIMES AT UPLOAD STATION

PHASE I SATELLITE VIEW TIMES AT UPLOAD STATION

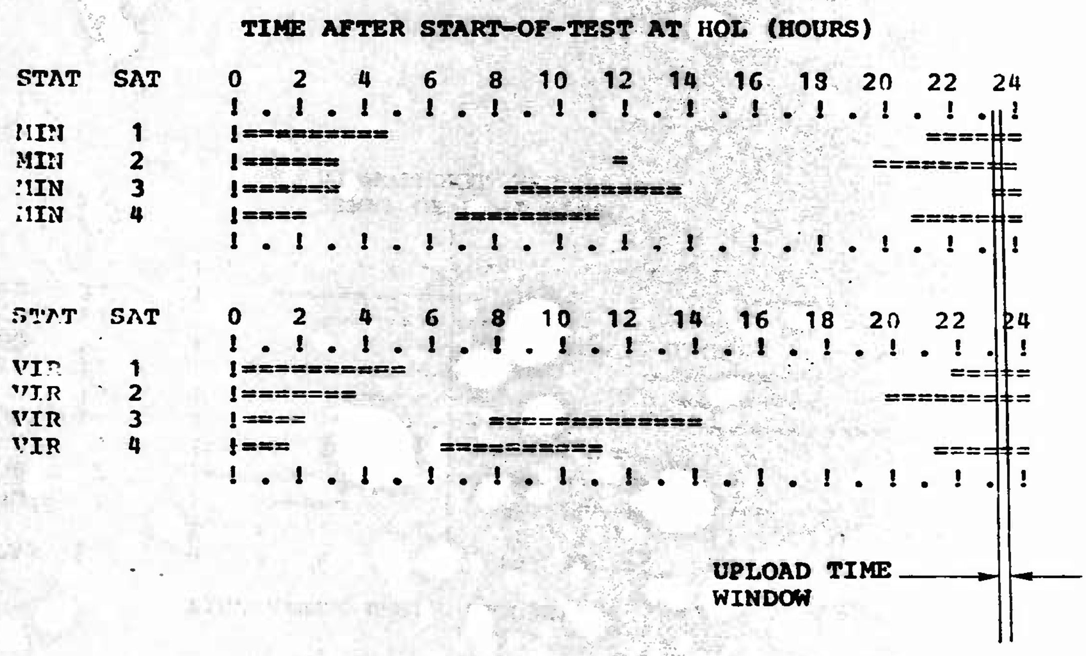


FIGURE 4-33 PHASE I SATELLITE VIEW TIMES AT UPLOAD STATION

PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

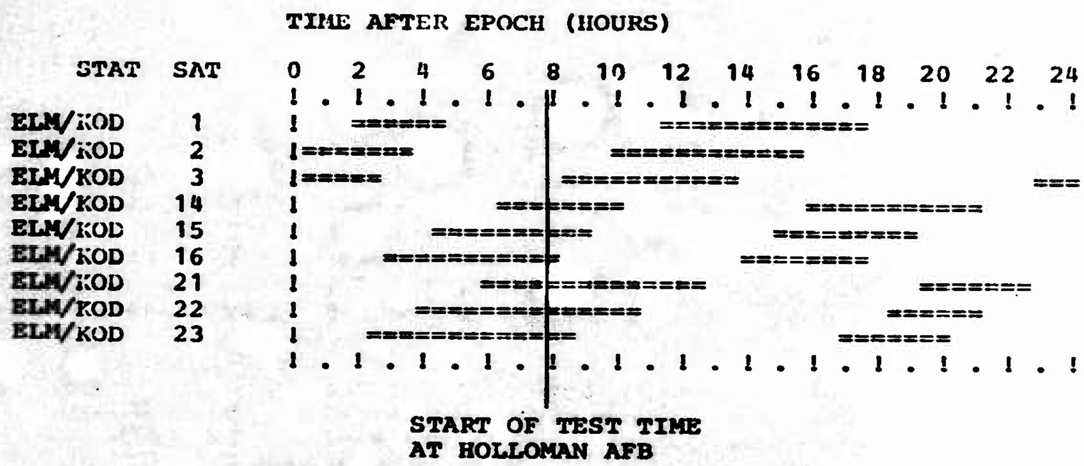


FIGURE 4-34 PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

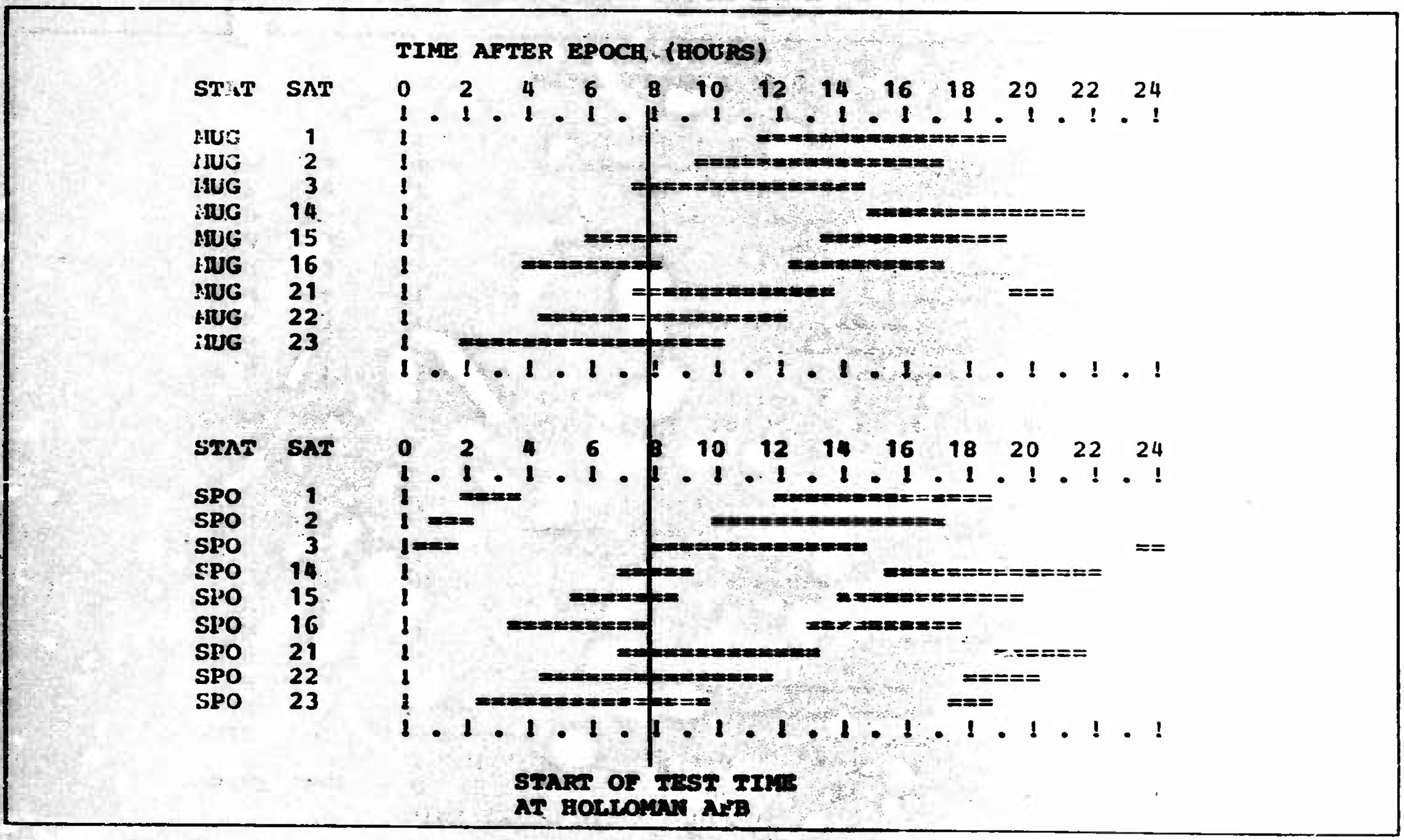


FIGURE 4-35 PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

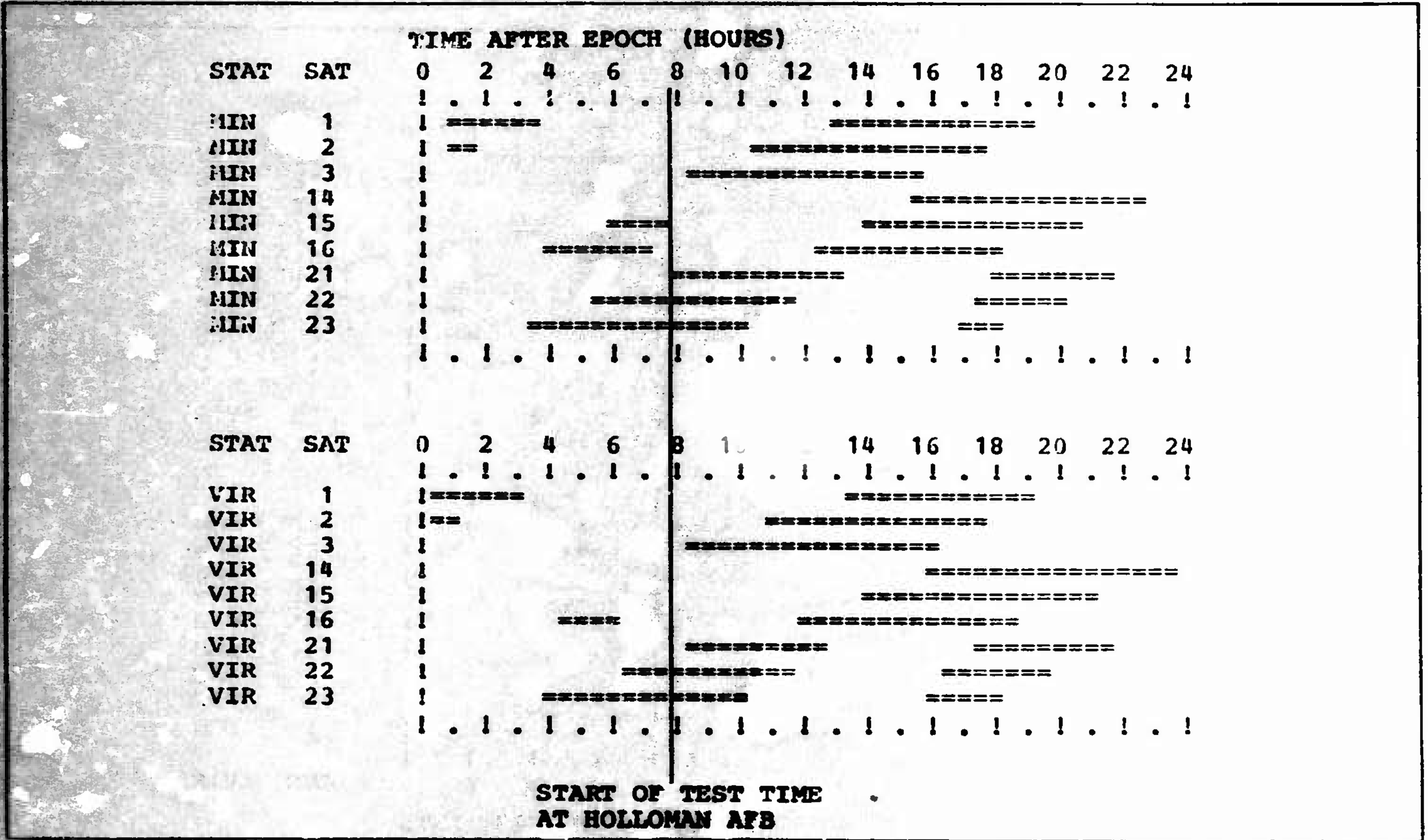


FIGURE 4-36 PHASE IIA SATELLITE VIEW TIMES OVER UPLOAD STATION

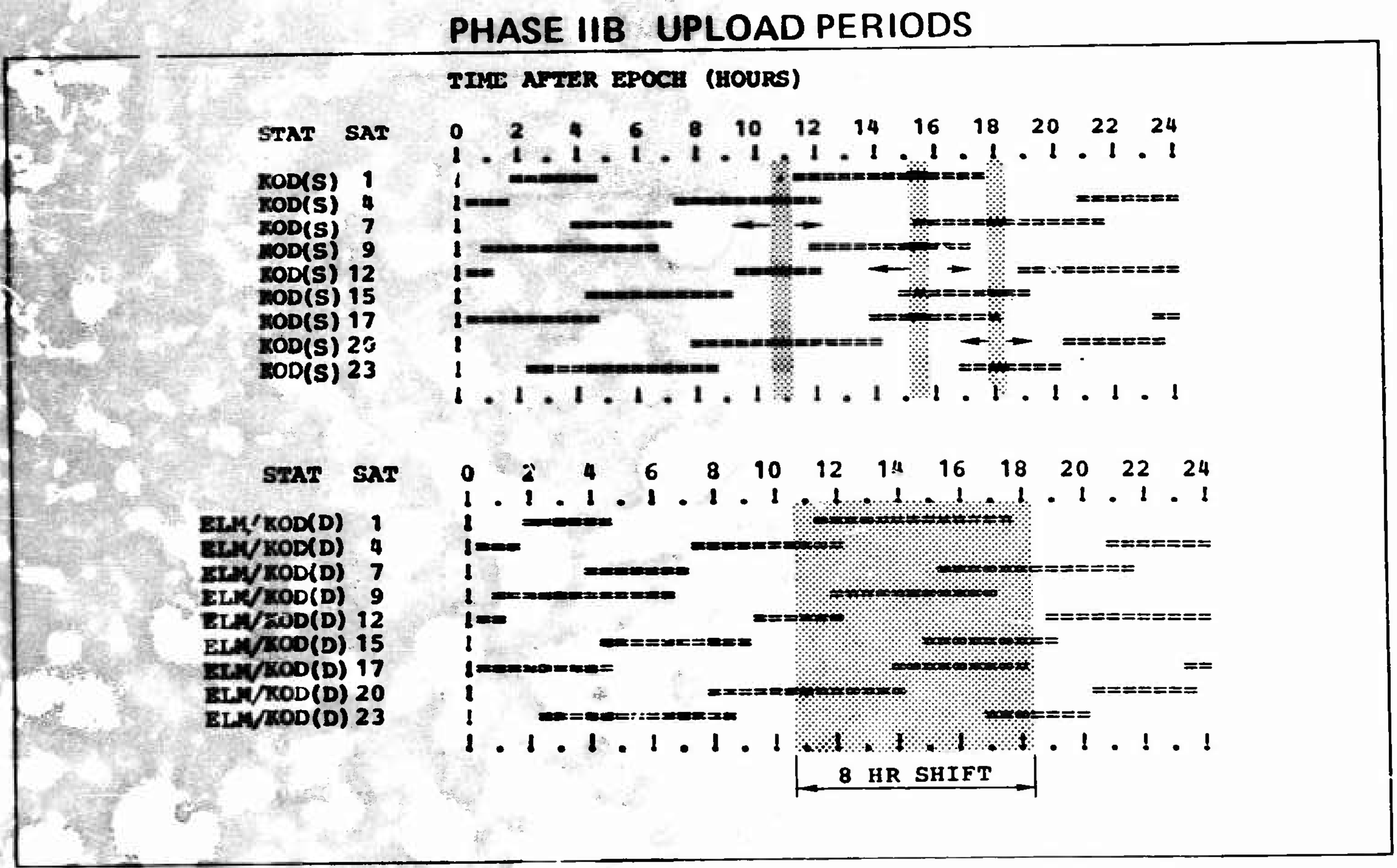


FIGURE 4-37 PHASE IIB UPLOAD PERIODS

PHASE IIB UPLOAD PERIODS

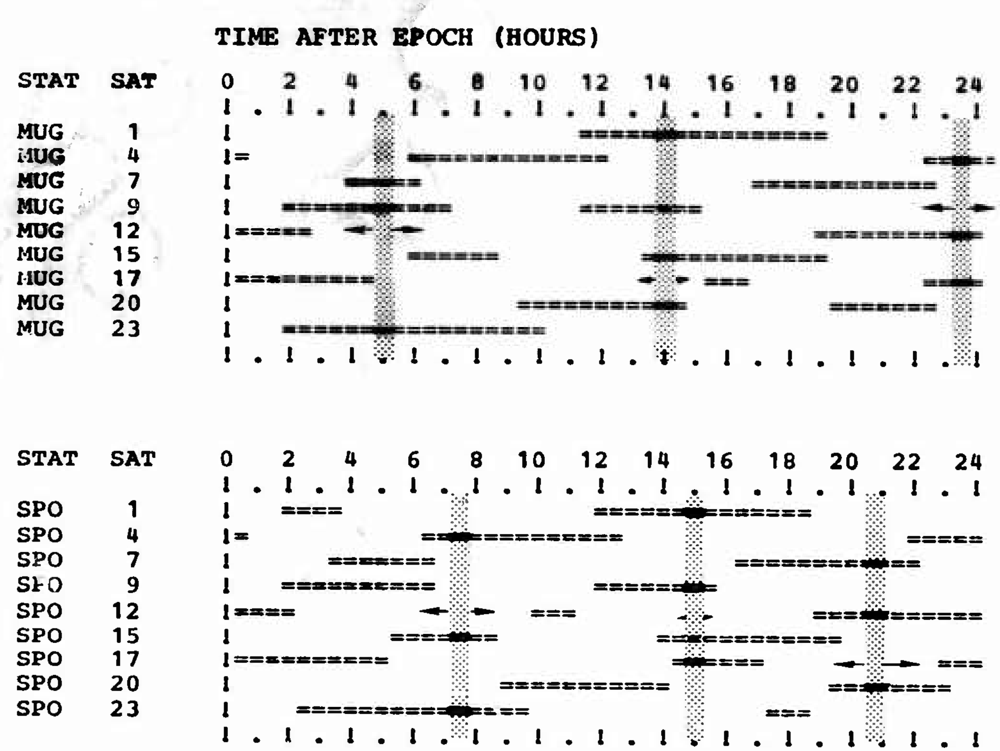


FIGURE 4-38 PHASE IIB UPLOAD PERIODS

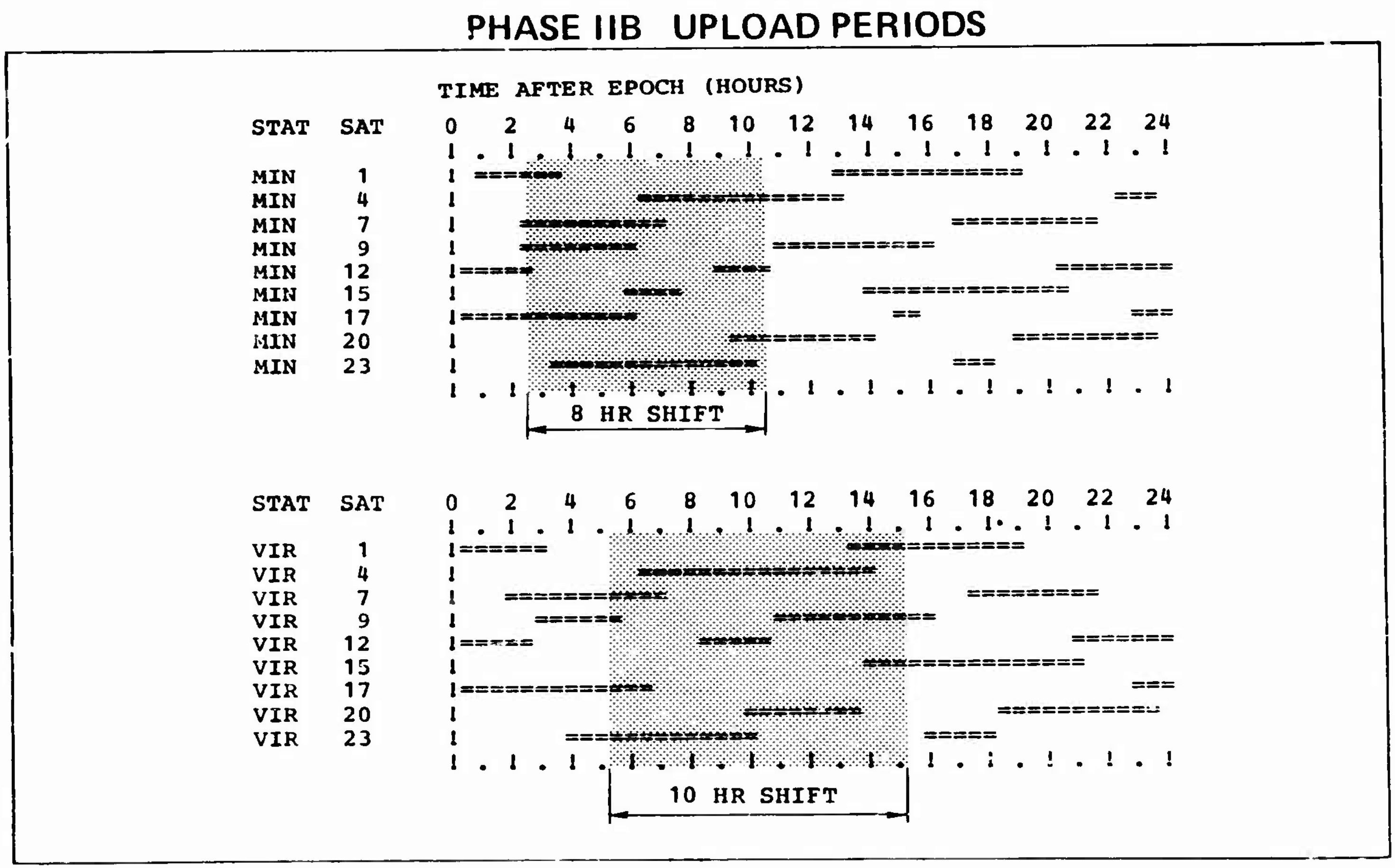


FIGURE 4-39 PHASE IIB UPLOAD PERIODS

PHASE III UPLOAD PERIODS

FIGURE 15

SATELLITE VIEW PERIODS AT KOD (SHARED)
ELEVATION ANGLE GREATER THAN: 5 DEG

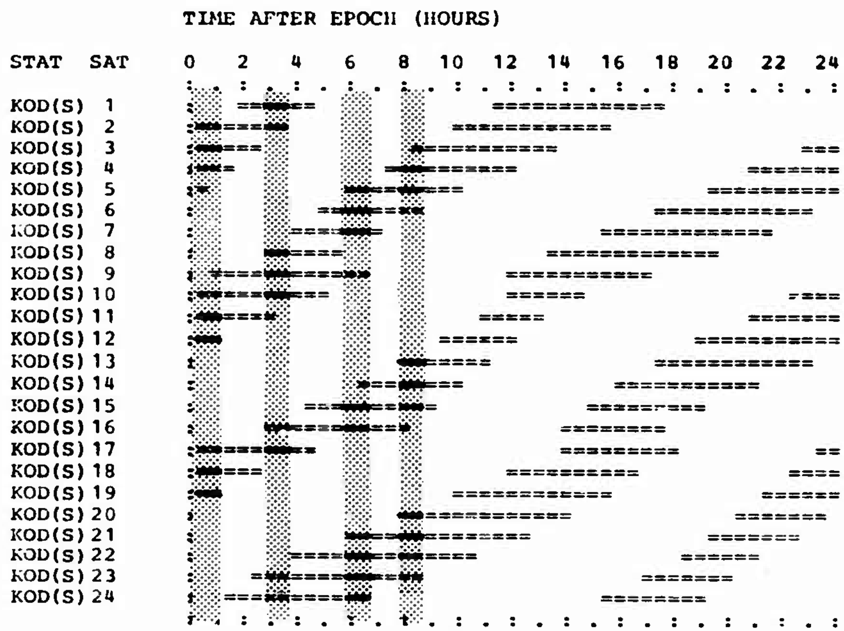


FIGURE 4-40 PHASE III UPLOAD PERIODS

PHASE III UPLOAD PERIOD

FIGURE 15

SATELLITE VIEW PERIODS AT KOD (DEDICATED) OR ELM
ELEVATION ANGLE GREATER THAN: 5 DEG

TIME AFTER EPOCH (HOURS)

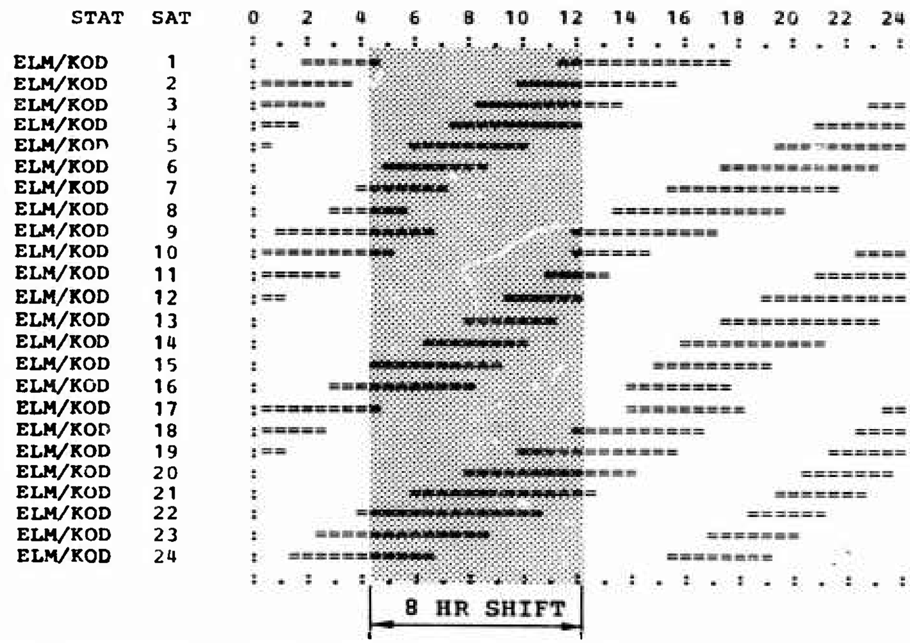


FIGURE 4-41 PHASE III UPLOAD PERIODS

PHASE III UPLOAD PERIODS

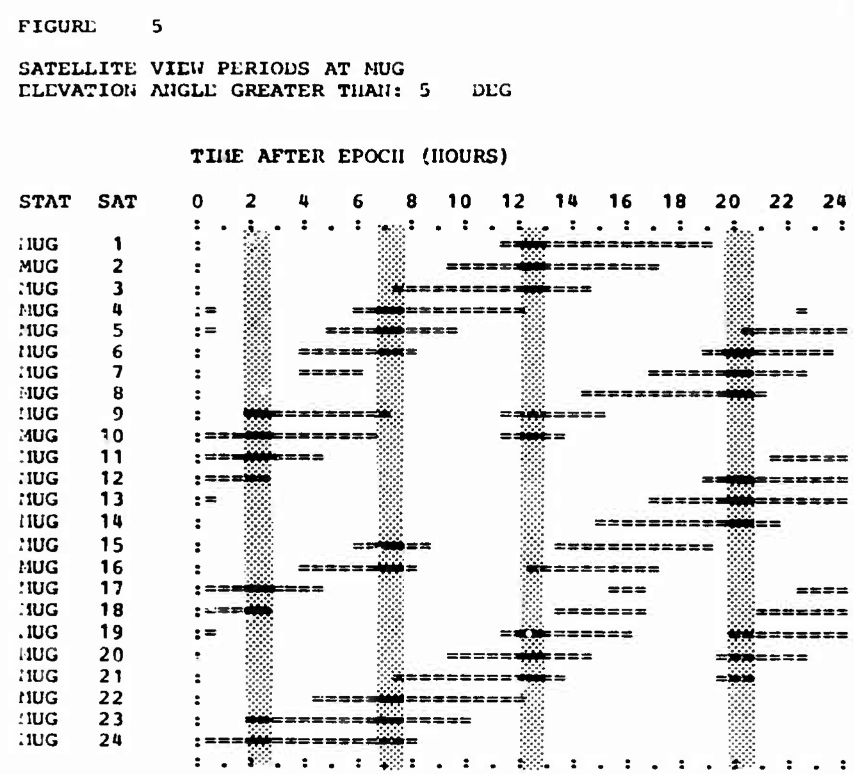


FIGURE 4-42 PHASE III UPLOAD PERIODS

PHASE III UPLOAD PERIODS

FIGURE 3

SATELLITE VIEW PERIODS AT SPO
ELEVATION ANGLE GREATER THAN: 5 DEG

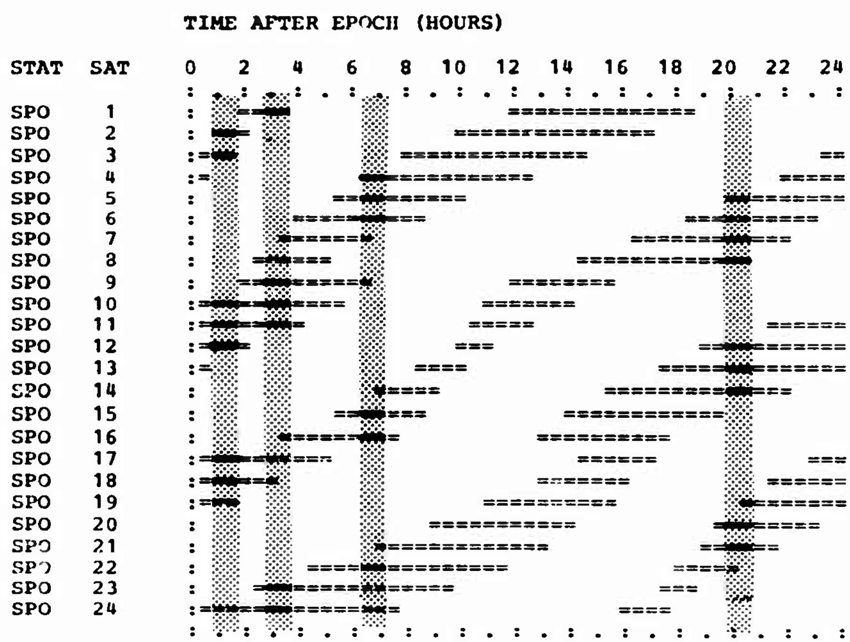


FIGURE 4-43 PHASE III UPLOAD PERIODS

PHASE III UPLOAD PERIOD

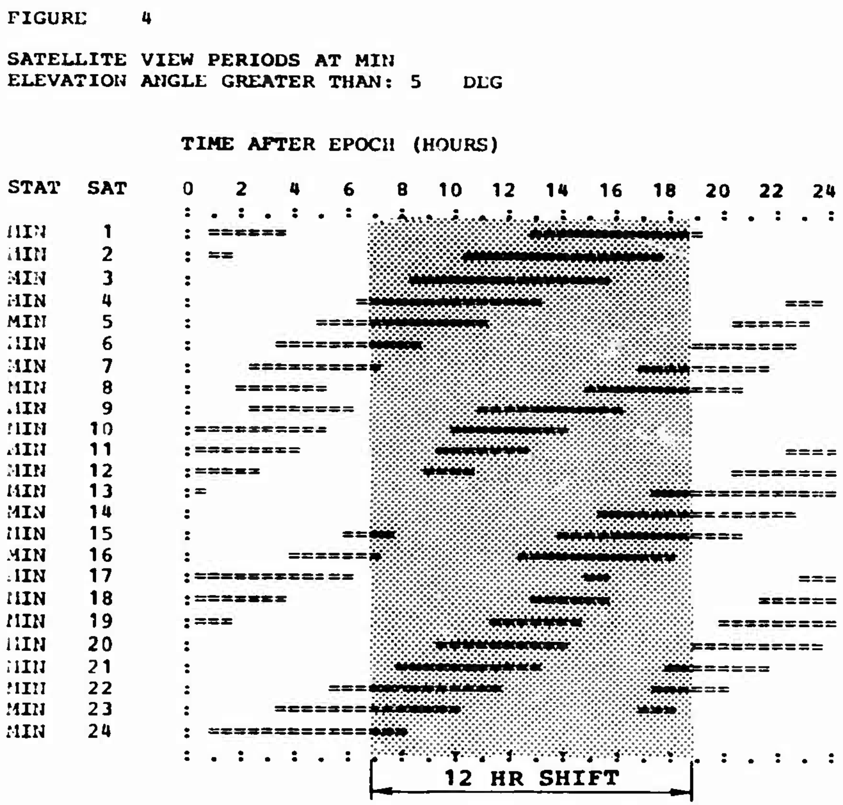


FIGURE 4-44 PHASE III UPLOAD PERIODS

PHASE III UPLOAD PERIOD

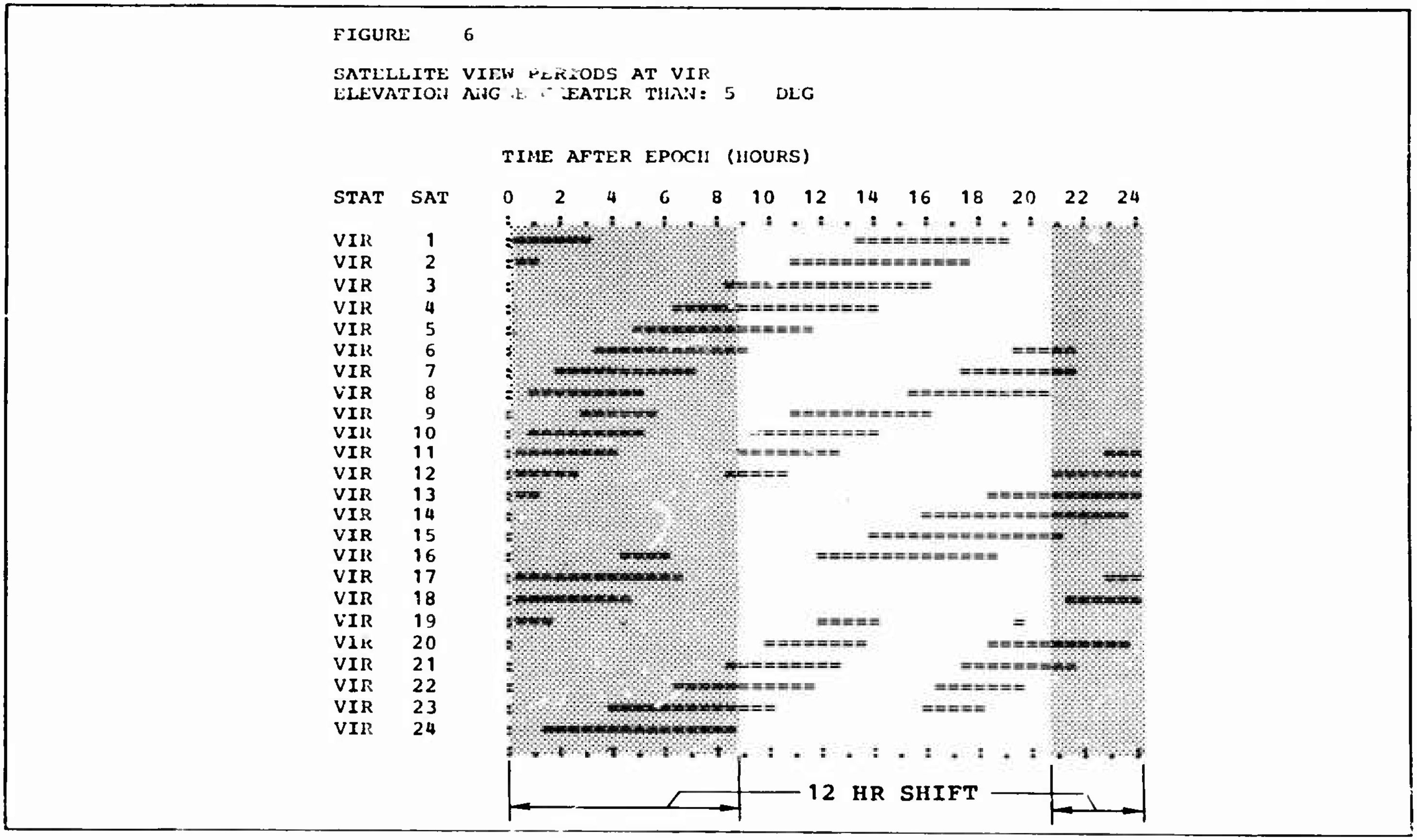


FIGURE 4-45 PHASE III UPLOAD PERIODS

UPLOAD CONCLUSIONS

	PHASE IIA	PHASE IIB	PHASE III
SHARED FACILITY (KOD-S, MUG, SPO)	NO. OF SATELLITES IN VIEW 12 HRS PRIOR TO TEST TIME KOD 9 ELM 9 MUG 7 SPO 9 MIN 8 VIR 8	3 40 MIN UPLOAD PERIODS (3 SATELLITES EA)	4 60 MIN UPLOAD PERIODS (6 SATELLITES EA)
DEDICATED FACILITY (ELM, KOD-D, VIR, MIN)		ONE 8 HR SHIFT AT ALL STATIONS EXCEPT VIR (10 HR SHIFT REQ'D)	ONE 8 HR SHIFT AT ELM/KOD-D ONE 12 HR SHIFT AT VIR & MIN

FIGURE 4-46 UPLOAD CONCLUSIONS

5.0 Candidate Configurations

This section summarizes the analysis of the various configurations developed during this study. The major hardware/software elements which are common to all configurations are shown in Figure 5-1.

The initial analysis was based upon the following alternatives:

- SCF-1
- SCF-2
- SAC
- NAG
- NWL

Section 5.1 describes the essential characteristics of each of the above approaches and shows a cost comparison. The SCF-1 configuration was selected as the Philco-Ford baseline and presented at the December 18 TD meeting. Direction was then given to concentrate on the NAG and SCF alternatives.

Section 5.2 presents the results of the analysis of the following alternatives.

Designation	MCS	US
A	STC	KTS
B	STC	ELM
C	MUGU	SPO
D	MUGU	ELM
E	MUGU	MINN

A cost comparison showed alternative A was the least costly and was recommended at the January 8, 1974 status review meeting. Direction was given to concentrate on the NAG alternatives.

The six alternatives considered during the next iteration are given in Section 5.3 and were originally presented at the January 30, 1974 meeting. All of the alternatives are based upon the use of Pt. Mugu as the MCS. Direction was subsequently given to assume the use of VAFB as the MCS/US location. Part I, Volume C, Control Segment System Analysis Report, describes the system according to this latest direction.

MAJOR SOFTWARE/HARDWARE ELEMENTS

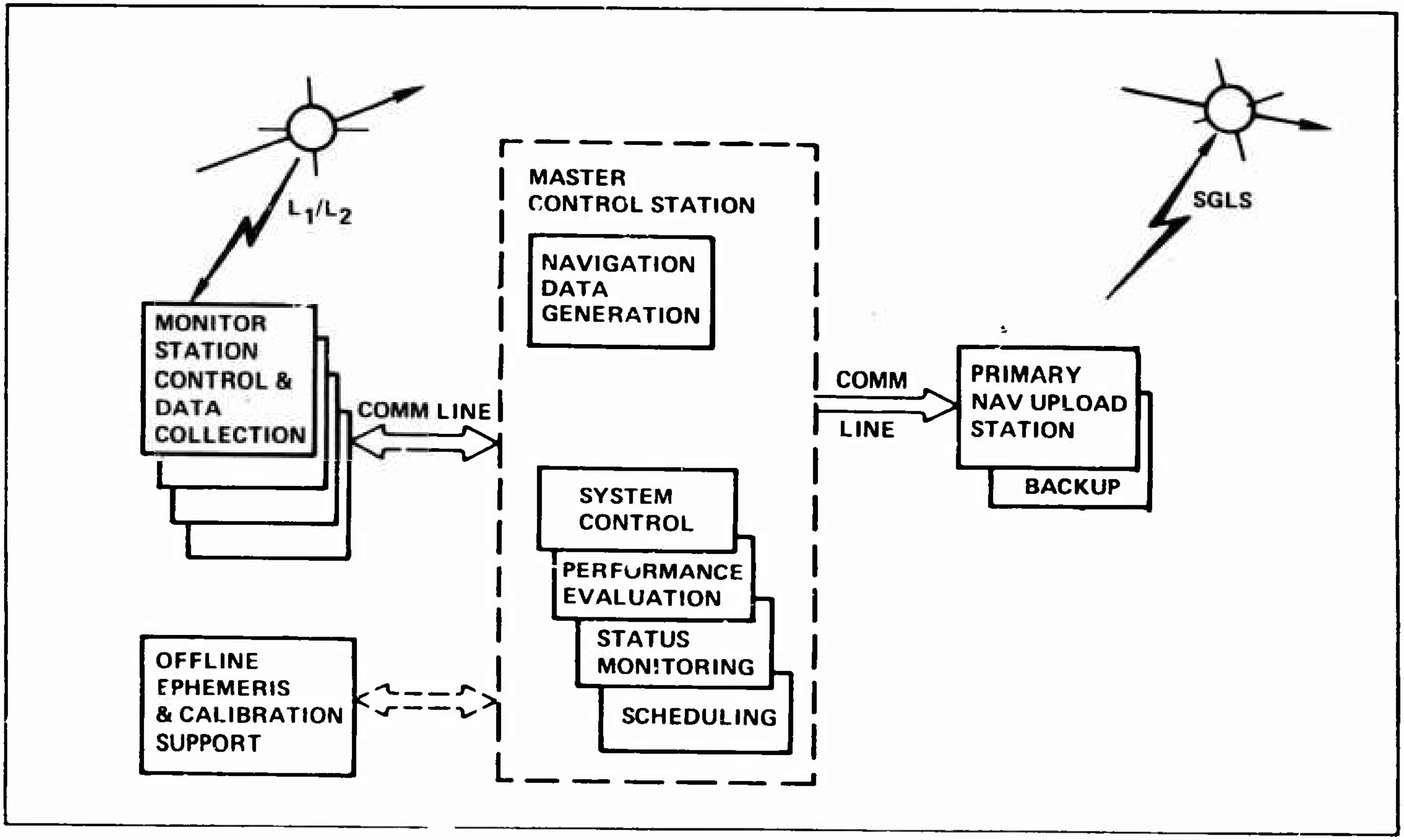


FIGURE 5-1 MAJOR SOFTWARE/HARDWARE ELEMENTS

5.1 Initial Configuration Analysis

The material in this section describes the analysis of the initial configurations.

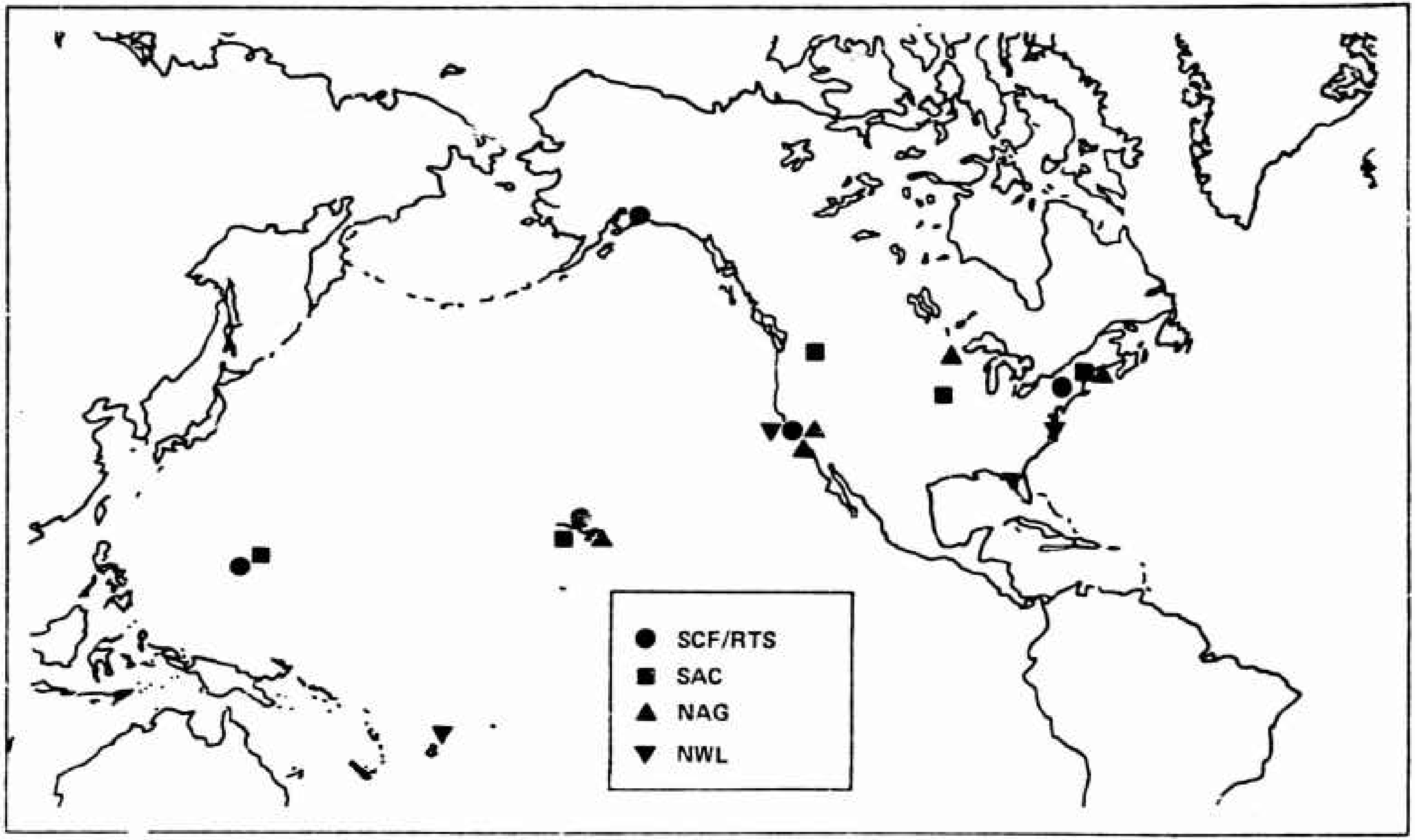


FIGURE 5-2 IDENTIFICATICN OF CANDIDATE C/S CONFIGURATIONS

FUNCTION \ SITE	KTS	VTS	HTS	NHS	STC	NWL
L-BAND SATELLITE TRACKING	X	X	X	X		
LAND LINE COMMUNICATION	X	X	X	X	X	X
SYSTEM CALIBRATION						X
REF. EPHEM. DETERMINATION						X
NAVIGATION DATA PROCESSING					X	
C/S CONTROL AND MONITORING					X	
SAT. NAV. DATA UPLOAD	X(P)	X(B)				
SAT. STATUS MONITORING					X	
SAT. TM AND COMMAND	X(P)	X(B)				

P = PRIME B = BACKUP

FIGURE 5-3 SCF NO. 1 CONTROL SEGMENT FUNCTIONAL ALLOCATION

FUNCTION / SITE	KTS	VAFB	HTS	NHS	STC	NWL
L-BAND SATELLITE TRACKING	X	X	X	X		
LAND LINE COMMUNICATION	X	X	X	X	X	X
SYSTEM CALIBRATION						X
REF. EPHEM. DETERMINATION						X
NAVIGATION DATA PROCESSING		X				
C/S CONTROL AND MONITORING		X				
SAT. NAV. DATA UPLOAD	X(B)	X(P)				
SAT. STATUS MONITORING		X				
SAT. TM AND COMMAND	X(B)	X(P)				

P = PRIME B = BACKUP

FIGURE 5-4 SCF NO. 2 CONTROL SEGMENT FUNCTIONAL ALLOCATION

FUNCTION / SITE	FAIR	LORI	GUAM	OMAHA	NWL
L-BAND SATELLITE TRACKING	X	X	X		
LAND LINE COMMUNICATION	X	X	X	X	X
SYSTEM CALIBRATION					X
REF. EPHEM. DETERMINATION					X
NAVIGATION DATA PROCESSING				X	
C/S CONTROL AND MONITORING				X	
SAT. NAV. DATA UPLOAD	X(P)	X(B)			
SAT. STATUS MONITORING				X	
SAT. TM AND COMMAND	X(P)	X(B)			

P = PRIME B = BACKUP

FIGURE 5-5 SAC CONTROL SEGMENT FUNCTIONAL ALLOCATION

FUNCTION \ SITE	PT MUGU	MAINE	HAWAII	MINN	NWL
L-BAND SATELLITE TRACKING	X	X	X	X	
LAND LINE COMMUNICATION	X	X	X	X	X
SYSTEM CALIBRATION					X
REF. EPHEM. DETERMINATION					X
NAVIGATION DATA PROCESSING	X				
C/S CONTROL AND MONITORING	X				
SAT. NAV. DATA UPLOAD	X(P)	X(B)			
SAT. STATUS MONITORING	X				
SAT. TM AND COMMAND	X(P)	X(B)			

P = PRIME   B = BACKUP

FIGURE 5-6 NAG CONTROL SEGMENT FUNCTIONAL ALLOCATION

FUNCTION / SITE	VAFB	VIR	RICH	SAMOA	NWL
L-BAND SATELLITE TRACKING	X	X	X	X	
LAND LINE COMMUNICATION	X	X	X	X	X
SYSTEM CALIBRATION					X
REF. EPHEM. DETERMINATION					X
NAVIGATION DATA PROCESSING					X
C/S CONTROL AND MONITORING					X
SAT. NAV. DATA UPLOAD	X(P)	X(B)			
SAT. STATUS MONITORING					X
SAT. TM AND COMMAND	X(P)	X(B)			

P = PRIME B = BACKUP

FIGURE 5-7 NWL CONTROL SEGMENT FUNCTIONAL ALLOCATION

FUNCTIONAL AREA	FUNCTIONS	EQUIPMENTS	MNEMONIC
L-BAND R&R TRACKING (MONITOR STATION)			$\boxed{L}$
	Satellite Tracking	4 Ch User Equip	$\boxed{L}$
	Comm	Timing	$\boxed{T}$
		Comm	$\boxed{C}$
UPLOAD STATION			$\boxed{U}$
	Sat. Nav Data Update	SGLS	$\boxed{S}$
	Sat TLM & CMD	Antenna	
	Comm	INY Encrypt	$\boxed{I}$
		Timing	$\boxed{T}$
		Comm Equip	$\boxed{C}$
MASTER CONTROL STATION			$\boxed{M}$
	Nav Data Proc	Nav Computer	$\boxed{N}$
	C/S Control & Mon	Displays	$\boxed{D}$
	Sat Status Mon	Comm Equip	$\boxed{C}$
	Comm		
REMOTE COMPUTER FACILITY			$\boxed{R}$
	Ref Ephem Determination	Ephem Computer	$\boxed{E}$
	System Cal	Comm	$\boxed{C}$
	Comm		

FIGURE 5-8 IDENTIFICATION OF FUNCTIONAL AREAS

SCF - 1

- TIME SHARE SCF COMM NET
- KTS MUST SUPPORT AT SCHEDULED TIMES

SCF-2

- SCF MUST RELEASE SPARE SGLS AND PRELORT
- TIME SHARE SCF COMM NET

SAC

- SIOP COMPUTER AVAILABLE EVERY 15 MIN FOR NAV PROC
- FAIR AND 1/2 OMAHA PLUS PERSONNEL FULLY SUPPORT GPS AT SCHEDULED TIMES

NAG AND NWL

- TIME SHARE COMM NET
- FACILITIES ARE AVAILABLE FOR SGLS EQUIPMENT AND MASTER CONTROL AT NO COST

FIGURE 5-9 CRITICAL ASSUMPTIONS

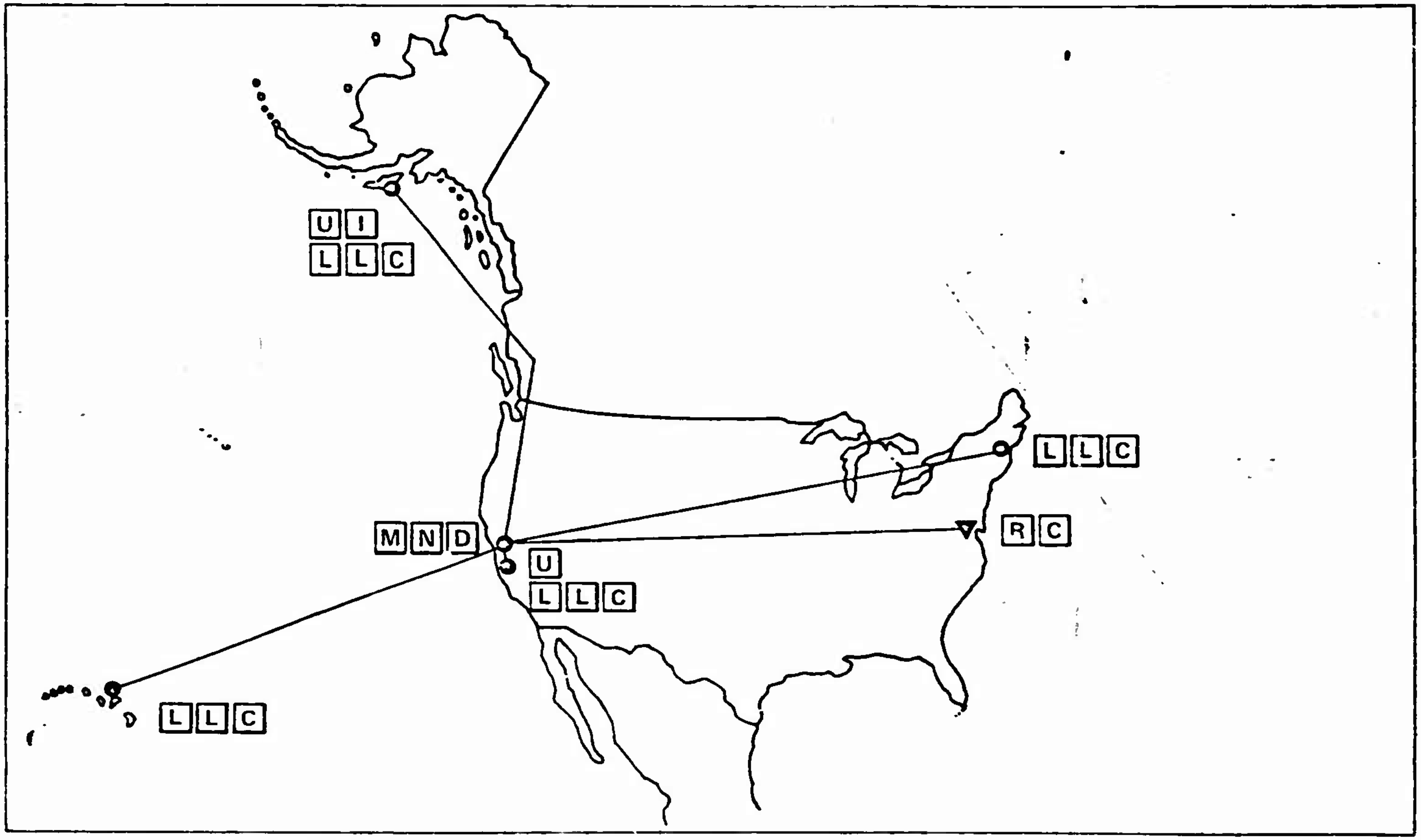


FIGURE 5-10 SCF 1 IMPLEMENTATION (BASELINE)

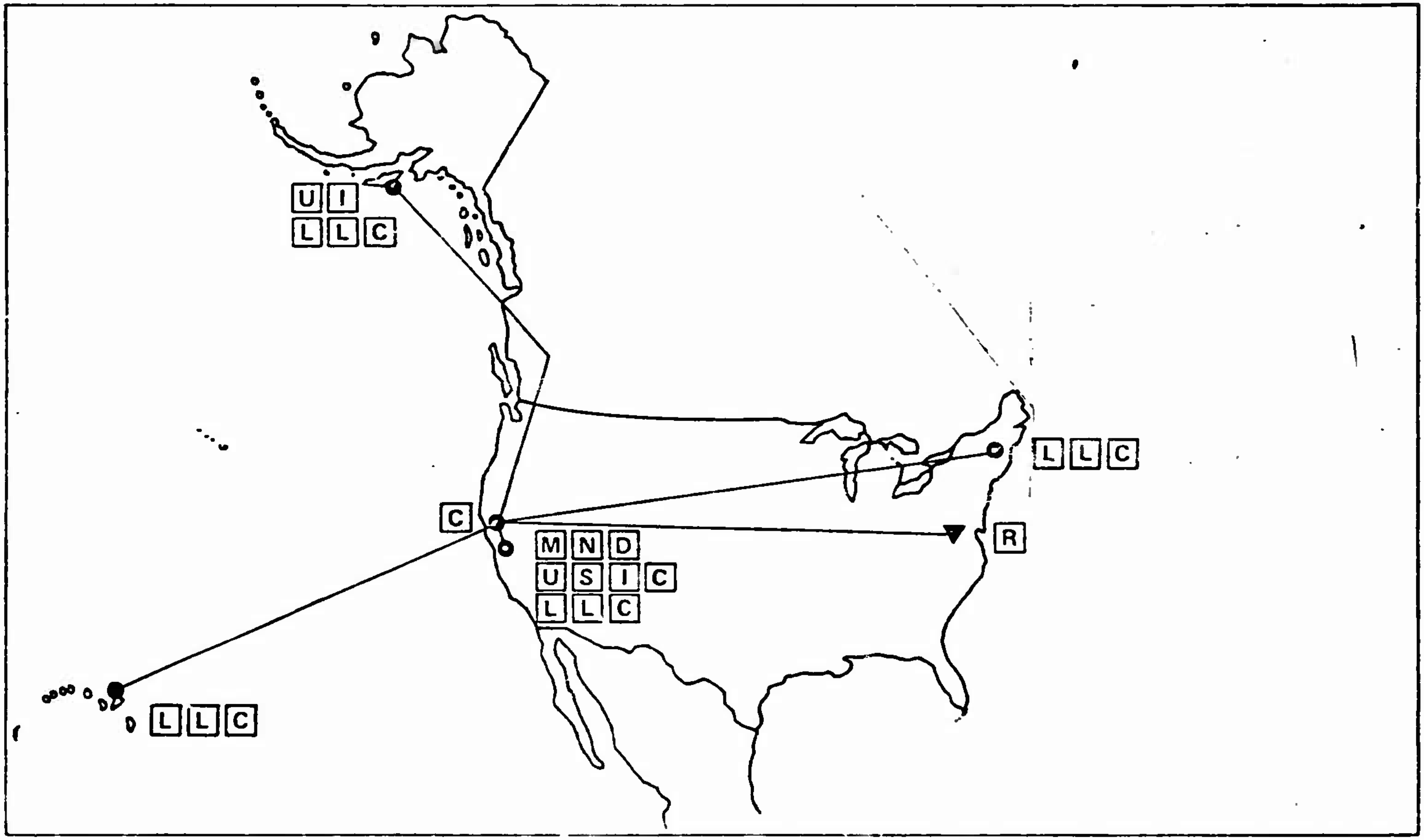


FIGURE 5-11 SCF 2 IMPLEMENTATION

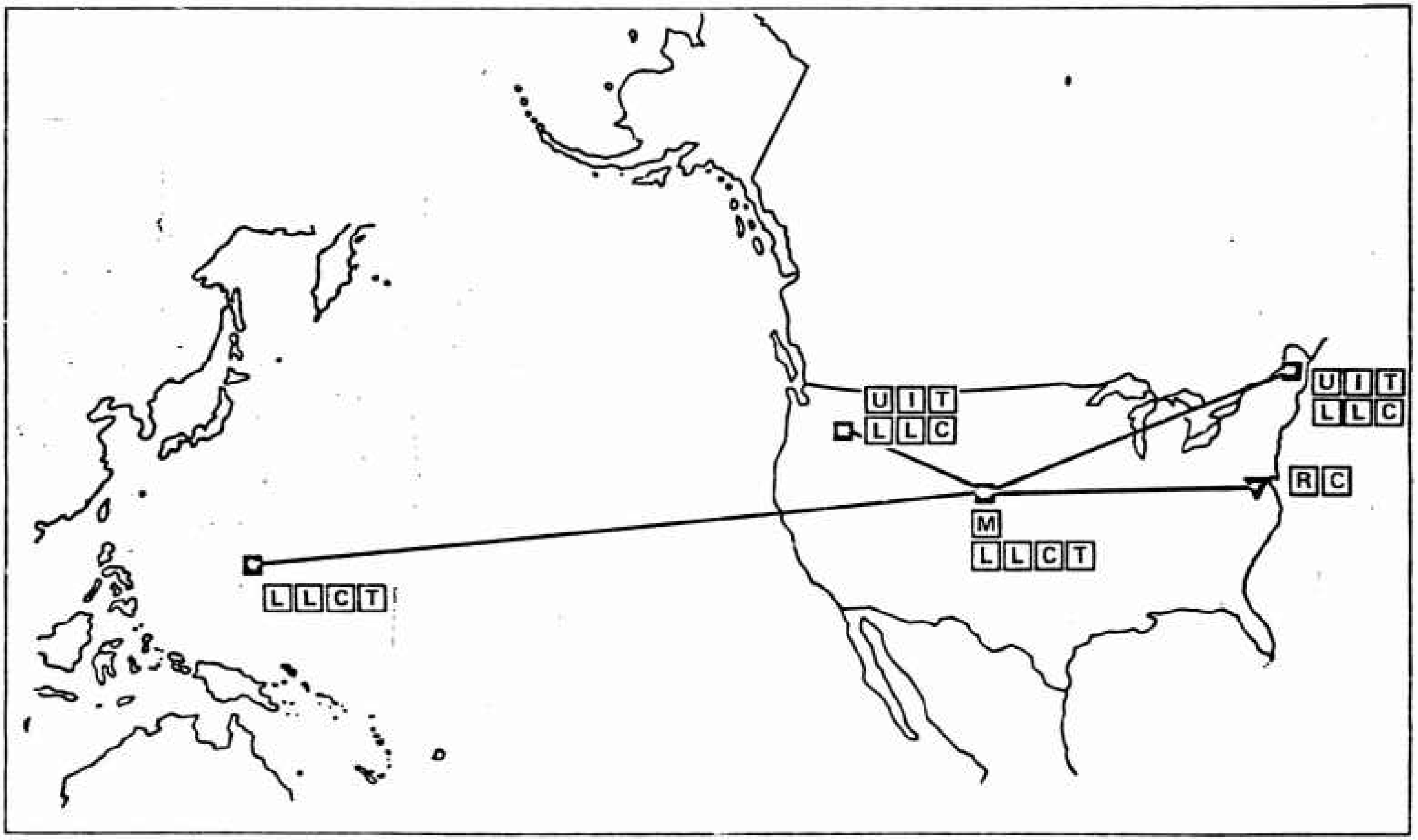


FIGURE 5-12 SAC IMPLEMENTATION

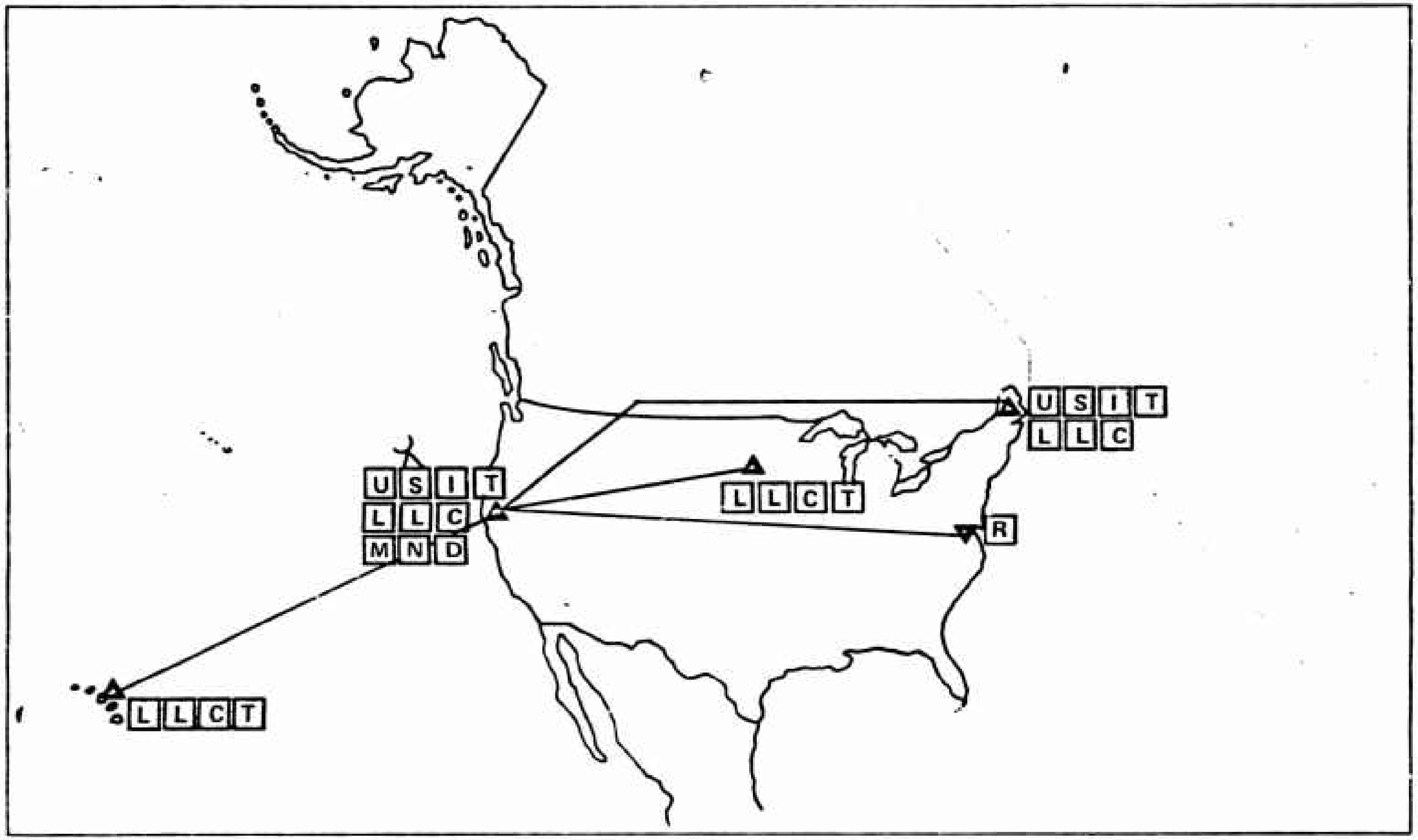


FIGURE 5-13 NAG IMPLEMENTATION

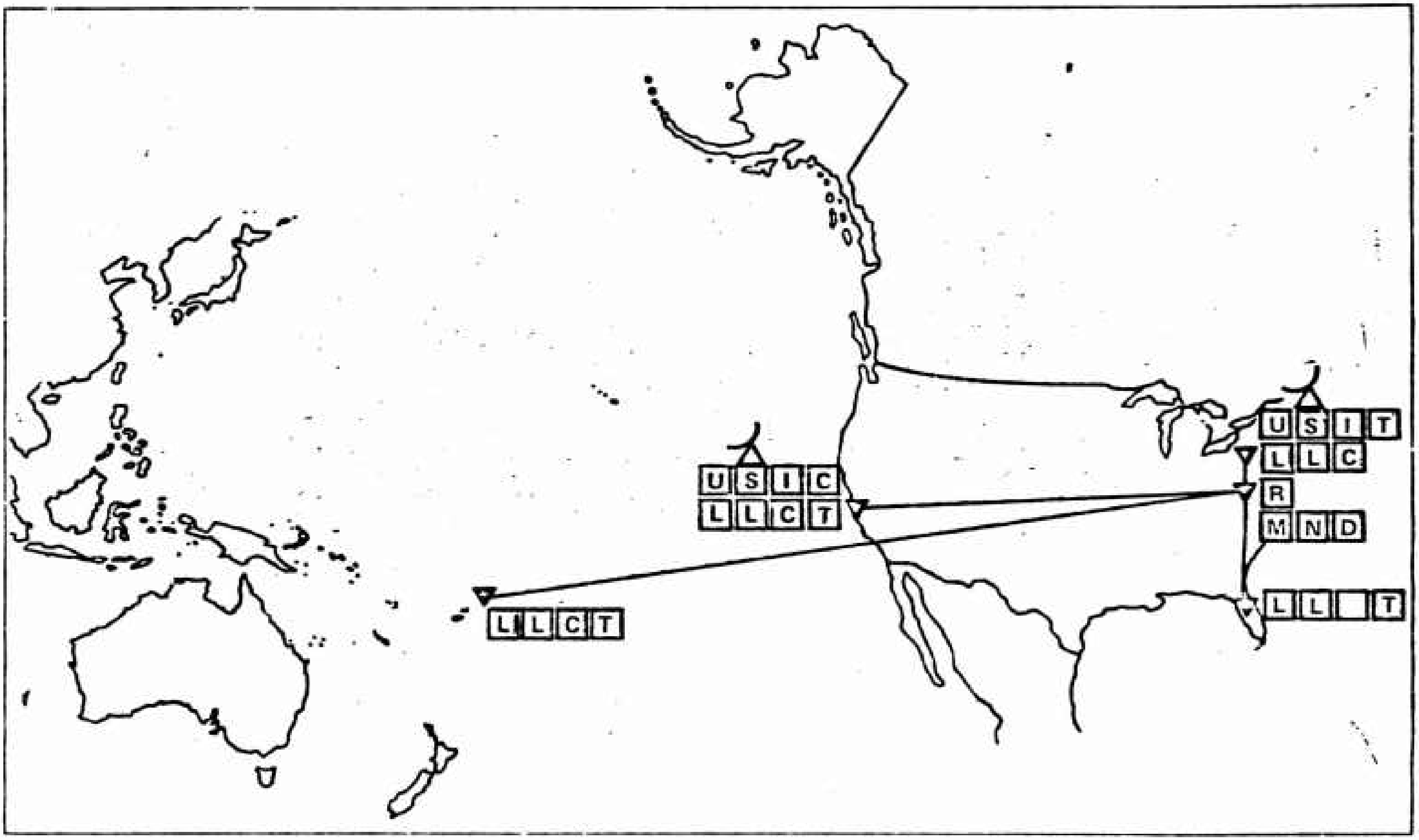


FIGURE 5-14 NWL IMPLEMENTATION

NON-RECURRING

- HARDWARE DESIGN & DEVELOPMENT
- SOFTWARE DESIGN & DEVELOPMENT
- SYSTEM ENGINEERING
- DOCUMENTATION COSTS
- FACTORY CHECKOUT
- PROCUREMENT
- HUMAN/SAFETY ENGINEERING, MAINTAINABILITY AND RELIABILITY
- COST ARE FOR PROTOTYPE DESIGN

RECURRING

- REMOTE COMPUTER FACILITIES ARE LEASED FOR $800/10 DAYS OVER A 2 YEAR PERIOD
  PHASE I OPERATIONS EXTEND OVER A 2 YEAR PERIOD

FIGURE 5-15 HARDWARE & SOFTWARE COST SUMMARY CRITERIA

MODIFICATION	SCF NO. 1	SCF NO. 2	SAC	NAG	NWL
L BAND R & R TRACKING 4 SITES • 4 CH USER EQUIP • TIMING • COMM	10.0 NR	10.0 NR	11.4 NR	11.4 NR	11.4 NR
UPLOAD STATION 2 SITES • SGLS • ANTENNA • INY • TIMING • COMM	1.5 NR	3.7 NR	7.4 NR	40.9 NR	40.9 NR
MASTER CONTROL STATION - 1 SITE • NAV COMP • DISPLAY • COMM	19.8 NR	20.3 NR	8.3 NR	19.8 NR	19.8 NR
REMOTE COMPUTER FACILITY • EPHEMERIS COMP • COMM	.6 R	.6 R	.6 R	.6 R	.6 R
TOTAL	31.3NR .6 R	34.0 NR .6 R	27.1 NR .6 R	72.1 NR .6 R	72.1 NR .6 R

FIGURE 5-16 HARDWARE AND SOFTWARE MODIFICATION COST SUMMARY

COST ELEMENTS	SCF NO. 1	SCF NO. 2	SAC	NAG	NWL
I&C - INCLUDES CHECKOUT, QA & TEST PROCEDURES	2.7 NR	2.7 NR	2.7 NR	9.0 NR	9.0 NR
FACILITIES - REFURBISH A/C				2.0 NR	
LAND LINE LEASE COST	TIME SHARE	TIME SHARE	TIME SHARE	TIME SHARE	SAMOA 3.12
LOGISTICS	8.8 NR	9.1 NR	5.9 NR	6.4 NR	6.4 NR
PERSONNEL	6.1 R	10.2 R	42.4 R	8.8 R	6.4 NR
TOTAL	11.5 NR 6.1 R	11.8 NR 10.2 R	10.6 NR 4.1 R	15.4 NR 8.8 R	18.5 NR 14.3 R
TOTALS FOR INSTALLATION & OPERATORS PLUS HARDWARE/SOFTWARE	42.8 NR 6.7 R 49.5	45.8 NR 10.8 R 56.6	37.7 NR 4.7 R 42.4	87.5 NR 9.4 R 96.9	90.6 NR 14.9 R 105.5

FIGURE 5-17 INSTALLATION AND OPERATION COST SUMMARY

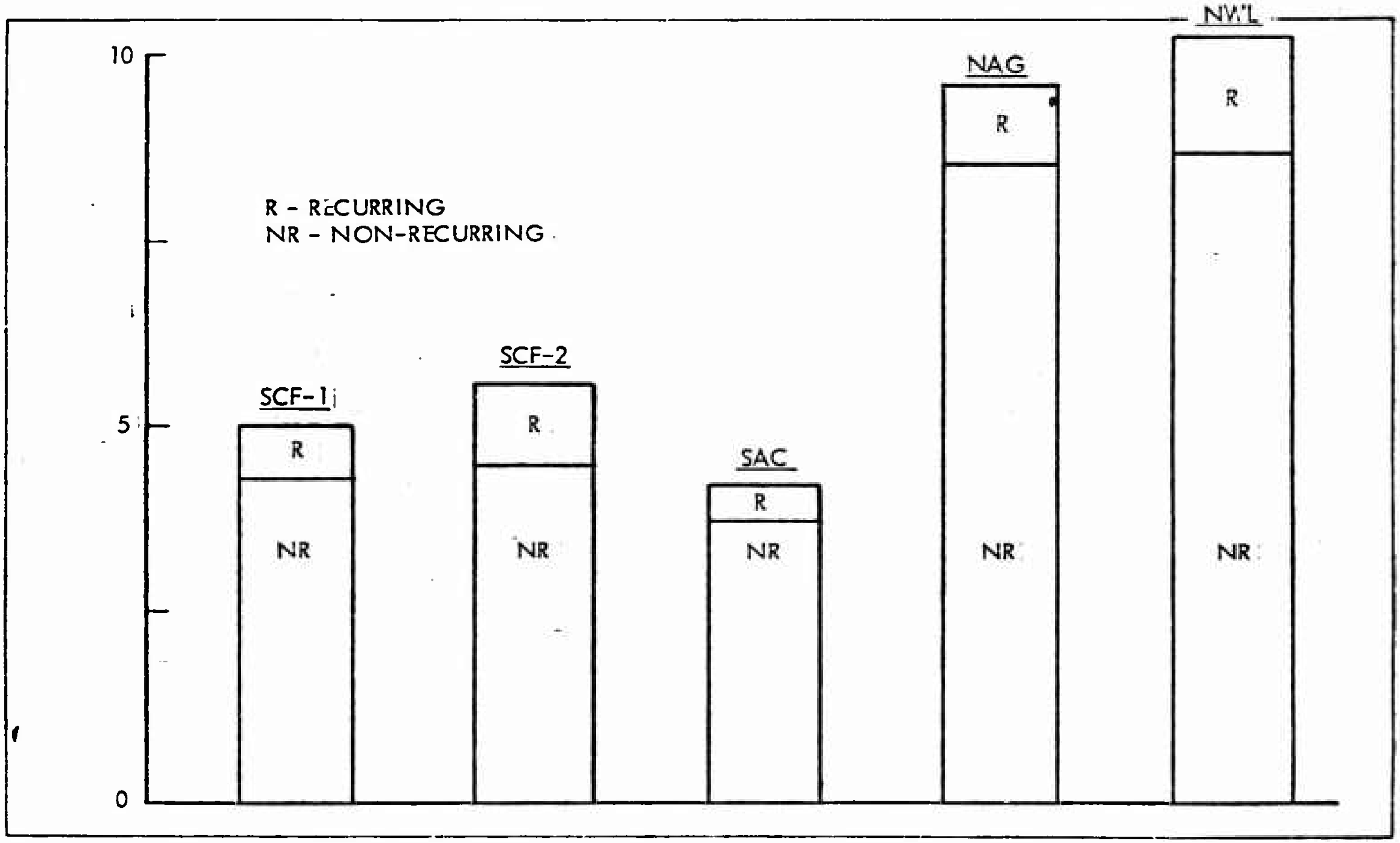


FIGURE 5-18 PHASE 1 GCS COSTS BY NETWORK

5.2 First Iteration

The material in this section summarizes the results of the configuration selection analysis conducted between December 18, 1973 and January 8, 1974.

FUNCTION / STATION TYPE	MASTER CONTROL STATION (MCS)	UPLOAD STATION (ULS)	MONITOR STATIONS (MON)	REMOTE COMPUTER FACILITY (RCF)	SATELLITE CONTROL FACILITY (SCF)
L-BAND SATELLITE TRACK	X	X	X		
LAND-LINE COMMUNICATIONS	X	X	X	X	X
SYSTEM CALIBRATION				X	
SYSTEM TIME STANDARD	X				
REF EPHEMERIS DETERMINATION				X	
NAVIGATION DATA PROCESSING	X				
CS OPERATIONS CONTROL	X				
SVS OPERATIONS CONTROL					X
SVS NAV DATA UPLOAD		X			
SVS TLM AND COMMAND		X			X

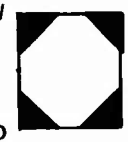
FIGURE 5-19 CONTROL SEGMENT FUNCTIONAL ALLOCATION

- DEMONSTRATE FULL RANGE OF POSSIBLE FACILITIES-MIXES
- DEMONSTRATE RANGE OF RECURRING/NON-RECURRING COST TRADES
- CONTRAST USE OF DEDICATED VS SHARED FACILITIES
- CONTRAST USE OF L-BAND VS SGLS TLM FOR UPLOAD VERIFICATION

FIGURE 5-20 CRITERIA FOR NOMINATING ALTERNATES

STATION \ CANDIDATE	A	B	C	D	E
MASTER CONTROL STATION (MCS)	STC	STC	MUGU	MUGU	MUGU
UPLOAD STATION (ULS)	*KTS	ELM	SPO	ELM	*MINN
MONITOR STATIONS					
NO. 1	HTS	HTS	*HAW	*HAW	*HAW
NO. 2	NHS	NHS	*MA	*MA	*MA
REMOTE COMPUTING FACILITY (RCF)	NWL	NWL	*NWL	*NWL	*NWL

KEY:



*COMM FROM MCS TO [ ]

FIGURE 5-21 CANDIDATE CONFIGURATIONS - PHASE I

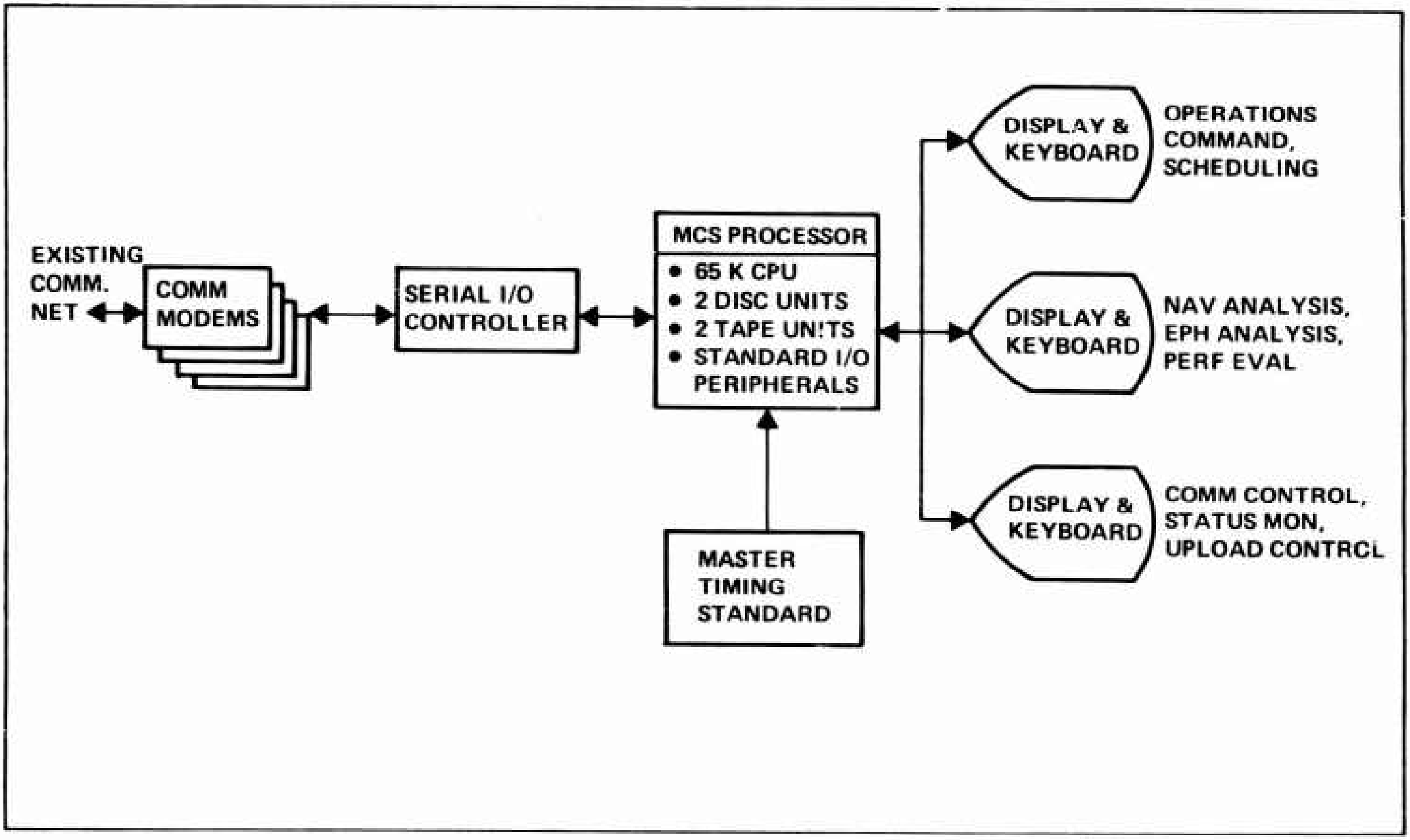


FIGURE 5-22 MASTER CONTROL STATION EQUIPMENT BLOCK DIAGRAM

CHARACTERISTICS \ CANDIDATES	A	B	C	D	E
LOCATION	KTS	ELM	SPO	ELM	MINN
SHARED	YES	NO	YES	NO	YES
SCF COMPATIBLE	YES	NO	NO	NO	NO
SGLS XMT	YES	YES	YES	YES	YES
SGLS RCV	YES	YES	YES	NO	NO
CESIUM STD	YES	NO	NO	NO	NO

FIGURE 5-23 UPLOAD STATION CANDIDATE CONFIGURATION

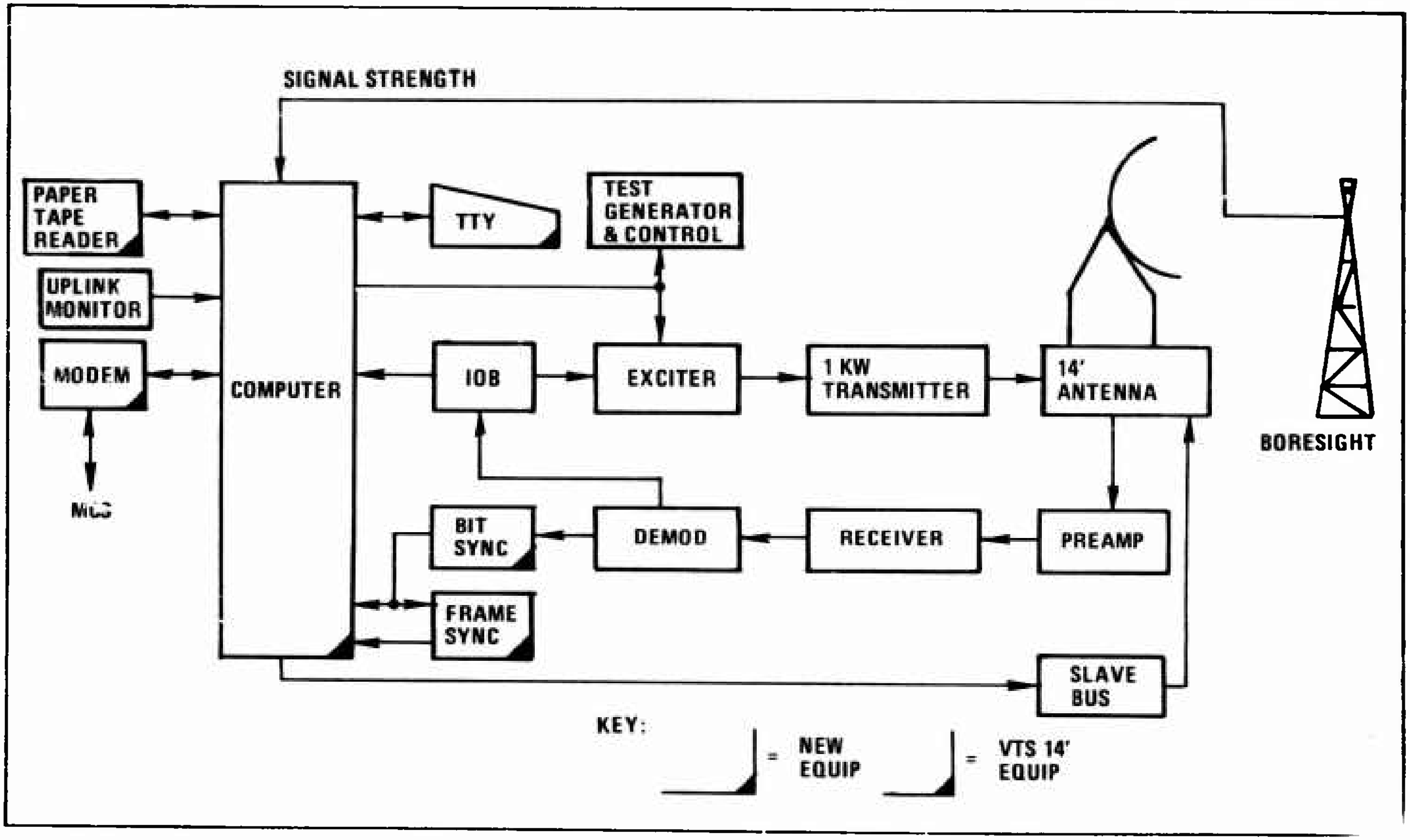


FIGURE 5-24 VTS RELOCATED TO ELMS

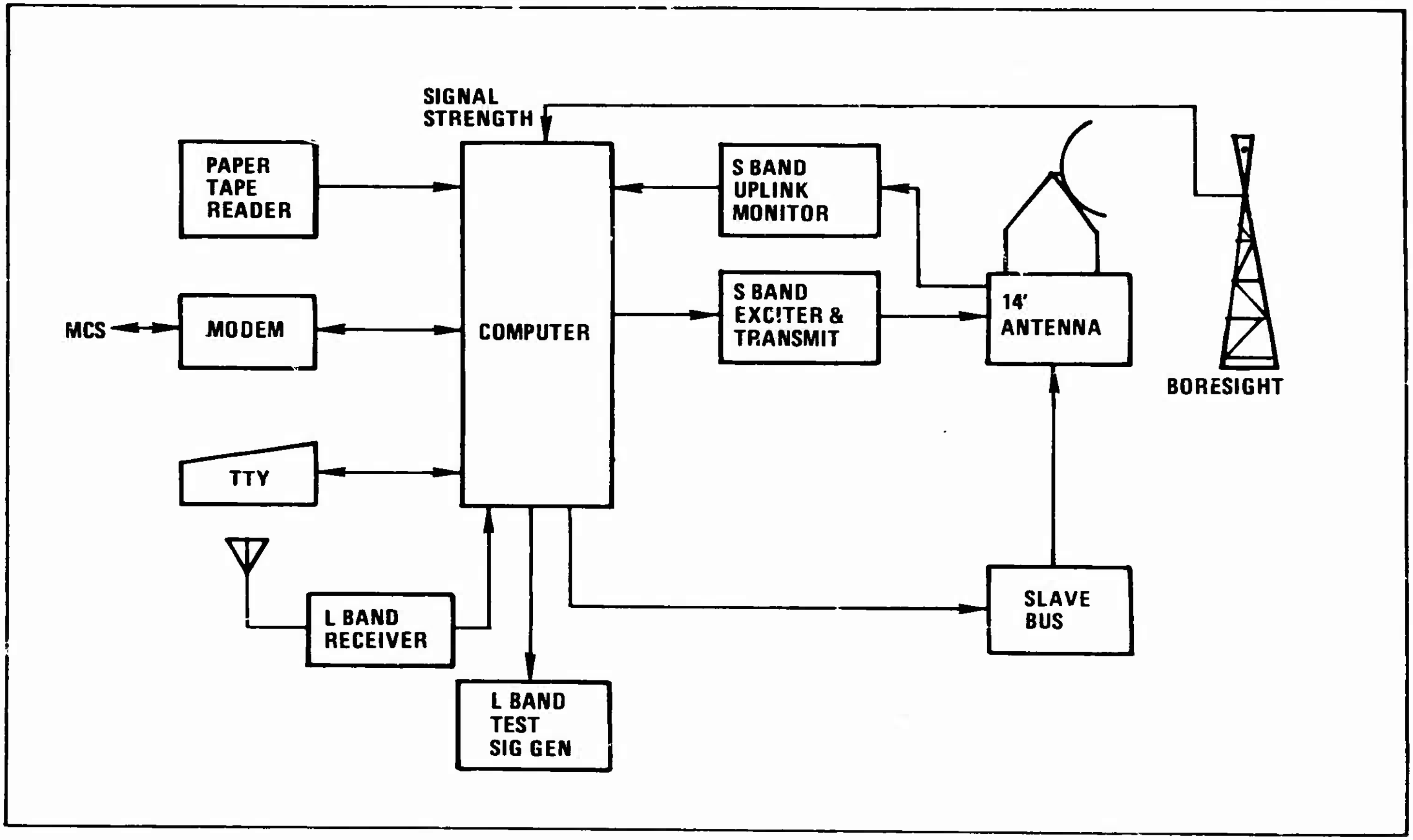
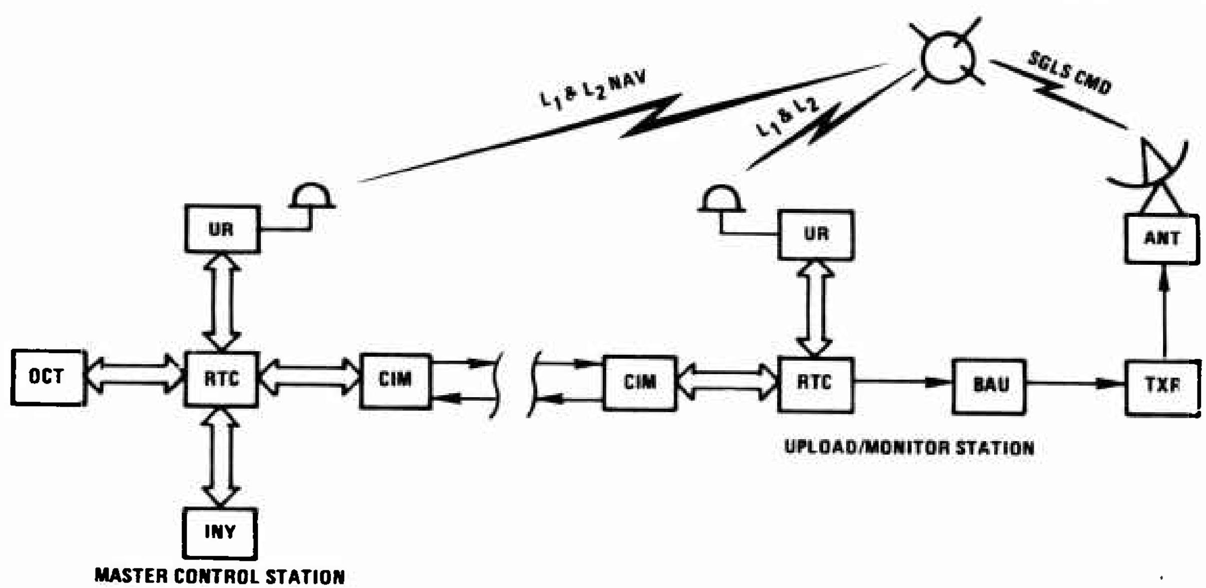


FIGURE 5-25 TRANSMIT ONLY AT ELM



KEY:

OCT = OPERATOR CONTROL TERMINAL
RTC = REAL-TIME CONTROLLER
UR = USER RECEIVER
CIM = COMMUNICATIONS INTERFACE AND MODEM
BAU = BASEBAND ASSEMBLY UNIT (SGLS)
TXR = TRANSMITTER-EXCITTER
ULS = UPLOAD STATION

FEATURES

- ULS TRANSPARENCY
- REAL-TIME OR STORE & FORWARD
- LOAD VERIFICATION VIA L-BAND
- ERROR CONTROL BY RETRANSMISSION
- REDUNDANT VERIFICATION MONITORING
- NO KG AT REMOTE SITES
- ALL COMMAND SOFTWARE AT MCS

FIGURE 5-26 BENT PIPE CONCEPT

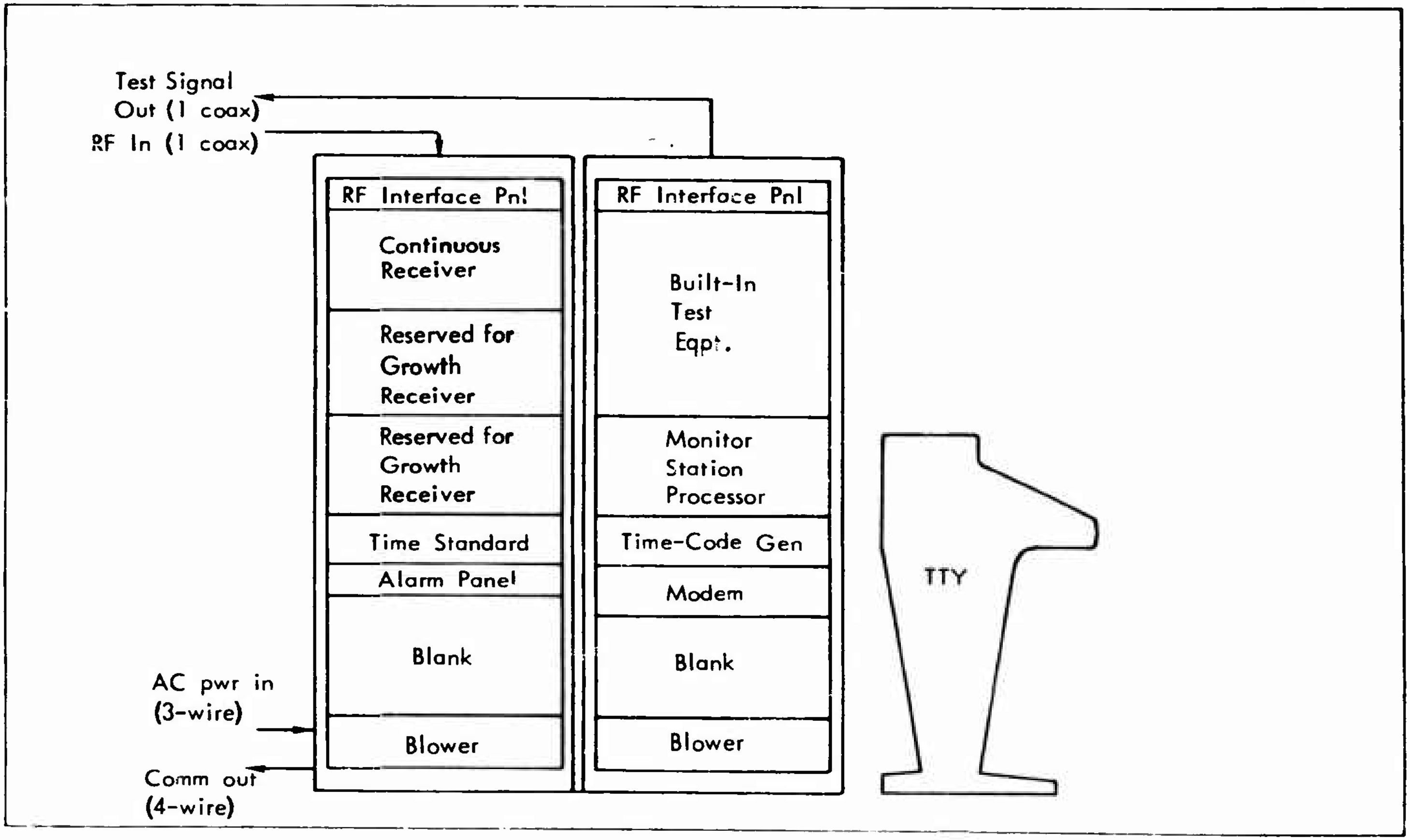


FIGURE 5-27 MONITOR STATION EQUIPMENT CONFIGURATION

- ADD SECOND 4-CHANNEL RECEIVER TO ALL MONITOR STATIONS
- INTEGRATE AND TEST HW/SW FOR ADDED SATELLITES
- ADD 1/2 SHIFT FOR EXPANDED OPERATIONS SCHEDULE
- INCREASE UPLOAD STATION TIME-ON-LINE
- RETAIN SCF BACKUP FOR T&C

FIGURE 5-28 UPGRADE FOR PHASE II

- REPLACE MONITOR RECEIVERS WITH 3 PRODUCTION MODELS PER SITE
- ADD REDUNDANT MCS DATA PROCESSING SYSTEM
- ADD REDUNDANT UPLOAD STATION
- RETAIN SCF BACKUP FOR T&C
- INCREASE PERSONNEL TO SUPPORT 4 SHIFTS, 24 HOUR OPERATIONS

FIGURE 5-29 UPGRADE FOR PHASE III

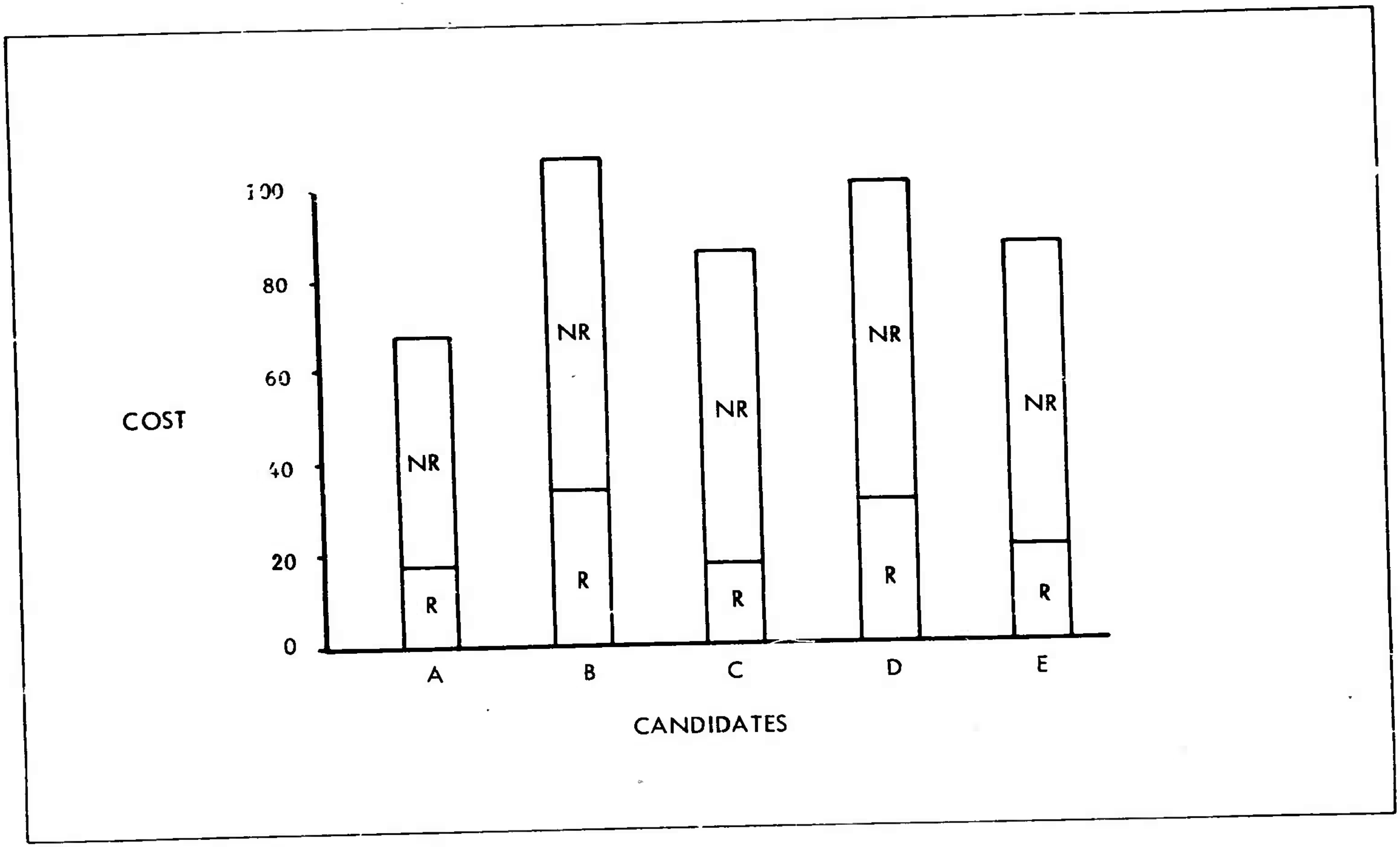


FIGURE 5-30 CONTROL SEGMENT COST TO END OF PHASE I

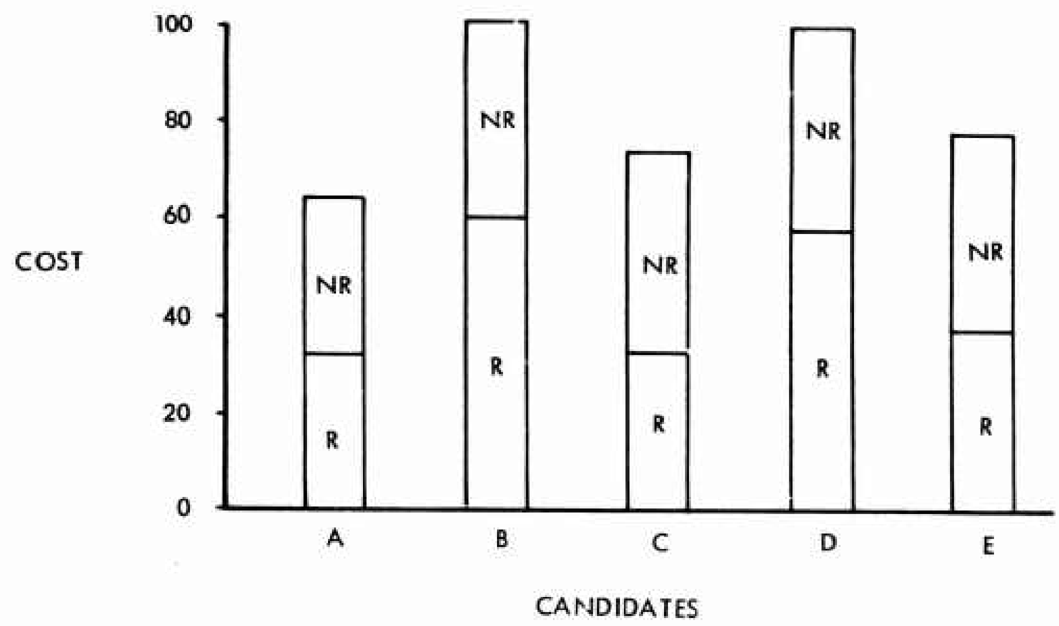


FIGURE 5-31 CONTROL SEGMENT COST TO END OF PHASE II

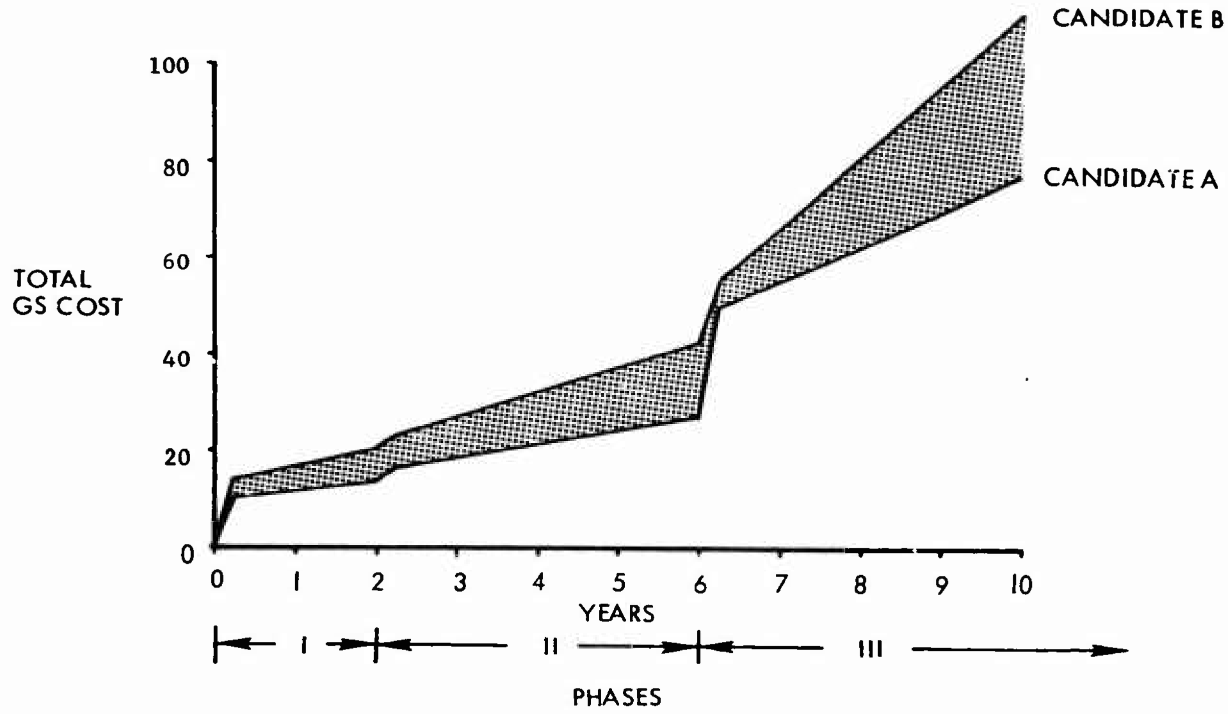


FIGURE 5-32 GROUND SEGMENT COST VS TIME

CANDIDATES / CRITERIA	A	B	C	D	E
PHASE I COST	5	1	3	1	3
LEGACY					
END OF PHASE II	5	1	3	1	3
AFTER 20 YEARS	5	1	3	1	2
ACCURACY	3	3	3	3	3
UPLOAD TIME	5	5	3	5	1
VULNERABILITY	5	3	4	3	3
AVAILABILITY	5	5	5	5	5
TECHNICAL RISK	5	3	1	3	3

1 - WORST, 5 - BEST

FIGURE 5-33 COMPARISON MATRIX

- DETERMINE DELTA $ DRIVERS BY PHASE
- MODIFY CONFIGURATIONS TO REDUCE DELTAS
- RE-EVALUATE CANDIDATES

FIGURE 5-34 SENSITIVITY ANALYSIS

PHASE	DELTA $ DRIVER
I	UPLOAD STATION INTEGRATION
II	UPLOAD STATION PERSONNEL
III	UPLOAD STATION PERSONNEL

FIGURE 5 55 COST SENSITIVITY ANALYSIS

PHASE I

- MCS AT MUGU FOR LEGACY: SHARED COMMUNICATION AND PERSONNEL
- MONITORS AT MUGU, HAW, MINN, MA TO SHARE COMM AND PERSONNEL
- ULS VIA STC/KTS TO MINIMIZE PHASE I COSTS
- ADD MUGU/STC COMM INTERFACE

PHASE II

- UPGRADE MINN TO TRANSMIT ONLY ULS
  WITH MINIMUM MANNING BENT PIPE APPROACH
- RETAIN BACK-UP SCF UPLOAD INTERFACE

PHASE III

- UPGRADE ALL MONITORS TO SGLS TX/RX MINIMUM MANNING CONFIGURATION
- ADD KIR-23 TO MCS
- TRANSFER SATELLITE T&C FROM SCF TO MCS
- TRANSFER EPHEMERIS SUPPORT FROM NWL TO MUGU/PMR

FIGURE 5-36 HYBRID APPROACH

- BEST USE OF EXISTING NAG RESOURCES FOR PHASE I
- BEST USE OF EXISTING AFSCF RESOURCES FOR PHASE I
- MINIMUM PHASE I COST
- MINIMUM DEVELOPMENT RISK
- GRADUAL TRANSITION FROM SHARED FACILITIES TO DEDICATED NAG OPERATION
- MINIMUM TOTAL PROGRAM RECURRING COSTS

FIGURE 5-37 BENEFITS

5.3 Second Iteration

The material in this section summarizes the results of configuration selection analysis conducted between January 9, 1974 and January 30, 1974. The major trades concerned upload/verification techniques and hardware. Thus, the bulk of the configuration analysis material is contained in Section 1.4.3 Navigation Upload/Verification - Second Iteration. The conclusions shown in 5.3 are thus based upon material in the latter section, as well as upon the analysis shown here.

<table>
<tr><th>ALTERNATE
FUNCTION</th><th>A1</th><th>D1</th><th>D2</th><th>D3</th><th>D4</th><th colspan="2">D5</th></tr>
<tr><td>MASTER CONTROL STATION</td><td>MUG</td><td>MUG</td><td>MUG</td><td>MUG</td><td>MUG</td><td colspan="2">MUG</td></tr>
<tr><td>MONITOR STATIONS ①</td><td>MINN*</td><td>ELM</td><td>ELM</td><td>ELM</td><td>ELM</td><td colspan="2">MINN*</td></tr>
<tr><td>ULS STATION</td><td>KTS*</td><td>ELM</td><td>ELM</td><td>ELM</td><td>ELM</td><td>KTS</td><td>MINN</td></tr>
<tr><td>MCS/ULS INTERFACE</td><td>STC/BB</td><td>NEW</td><td>NEW</td><td>NEW</td><td>NEW</td><td rowspan="6">SAME AS A1</td><td rowspan="6">* SAME AS D2</td></tr>
<tr><td>UPLOAD TECHNIQUE</td><td>EXISTING SCF PRACTICE</td><td>INC SCF SECURE WORD</td><td>CS SECURE WORD</td><td>CS SECURE WORD</td><td>CS SECURE WORD</td></tr>
<tr><td>VERIFICATION LINK</td><td>SGLS</td><td>L-BAND</td><td>L-BAND</td><td>SGLS</td><td>SGLS</td></tr>
<tr><td>ULS SGLS RCVR</td><td>YES</td><td>NO</td><td>NO</td><td>YES</td><td>YES</td></tr>
<tr><td>CMD GEN SOFTWARE AT</td><td>KTS</td><td>ELM</td><td>MCS</td><td>ELM</td><td>MCS</td></tr>
<tr><td>K1-23</td><td>KTS</td><td>SCF</td><td>MCS</td><td>ELM</td><td>MCS</td></tr>
</table>

① ALL CANDIDATES HAVE MONITOR STATIONS AT MUGU*, MAINE*, HAWAII*
* SHARE EXISTING COMMUNICATIONS

FIGURE 5-38 CONTROL CONFIGURATION STUDY

PREFERRED BASELINE D1

- MASTER CONTROL STATION AT PT. MUGU
- UPLOAD CONTROL STATION AT ELMENDORF AFB
- MONITOR STATIONS AT PT. MUGU, ELMENDORF AFB, HAWAII, AND MAINE

ALTERNATE BASELINE A1

- SAME AS PREFERRED BASELINE EXCEPT THAT EXISTING SCF STATION AT KTS IS USED FOR UPLOADING

VARIATIONS ON THE PREFERRED BASELINE

- D2 EQUALS D1 PLUS INY MCS
- D3 EQUALS D1 PLUS S-BAND RECEIVE AT ULS
- D4 EQUALS D2 PLUS S-BAND RECEIVE AT ULS
- D5 EQUALS D2 PLUS A1

FIGURE 5-39 CANDIDATE CONFIGURATIONS

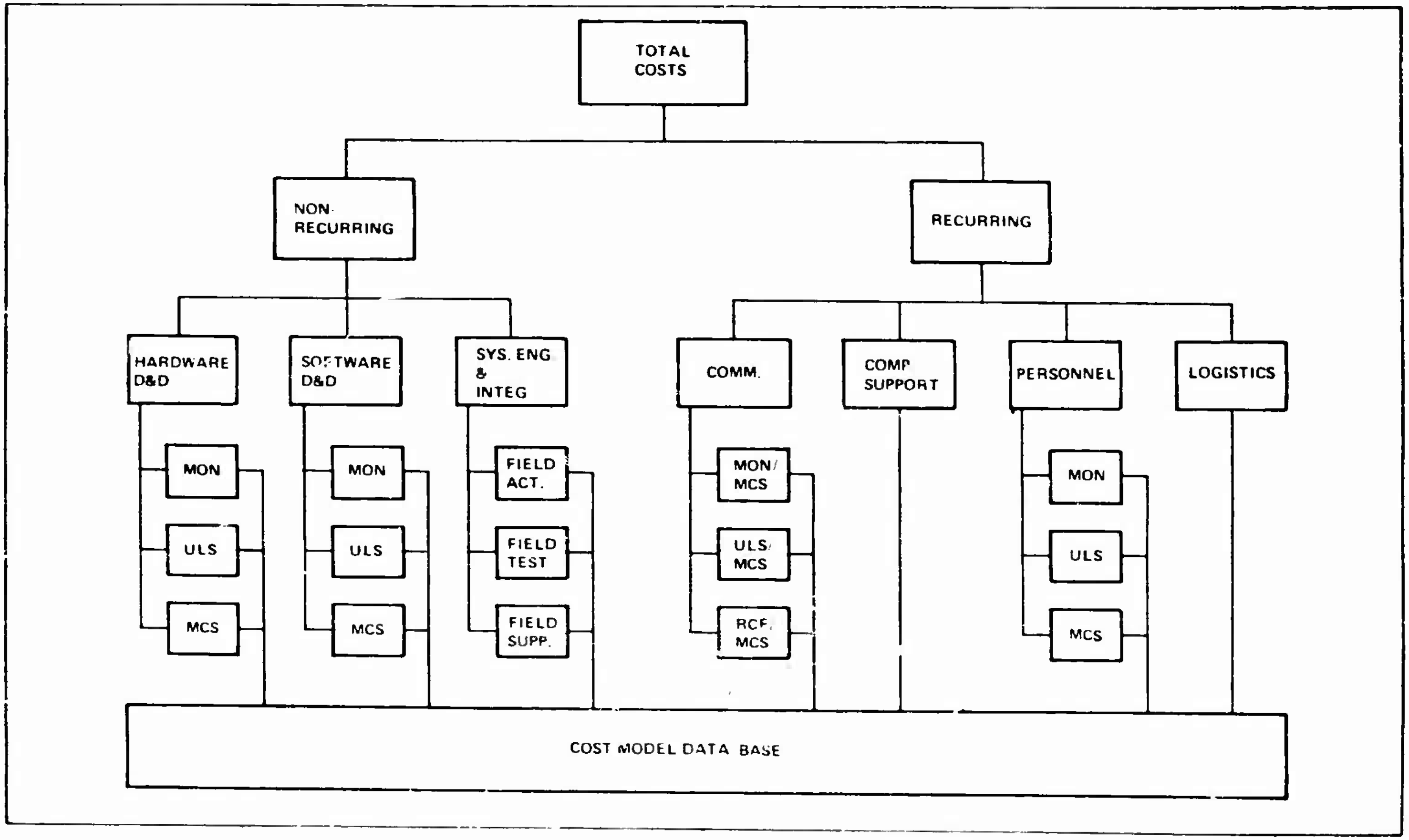


FIGURE 5-40 COST BREAKDOWN STRUCTURE

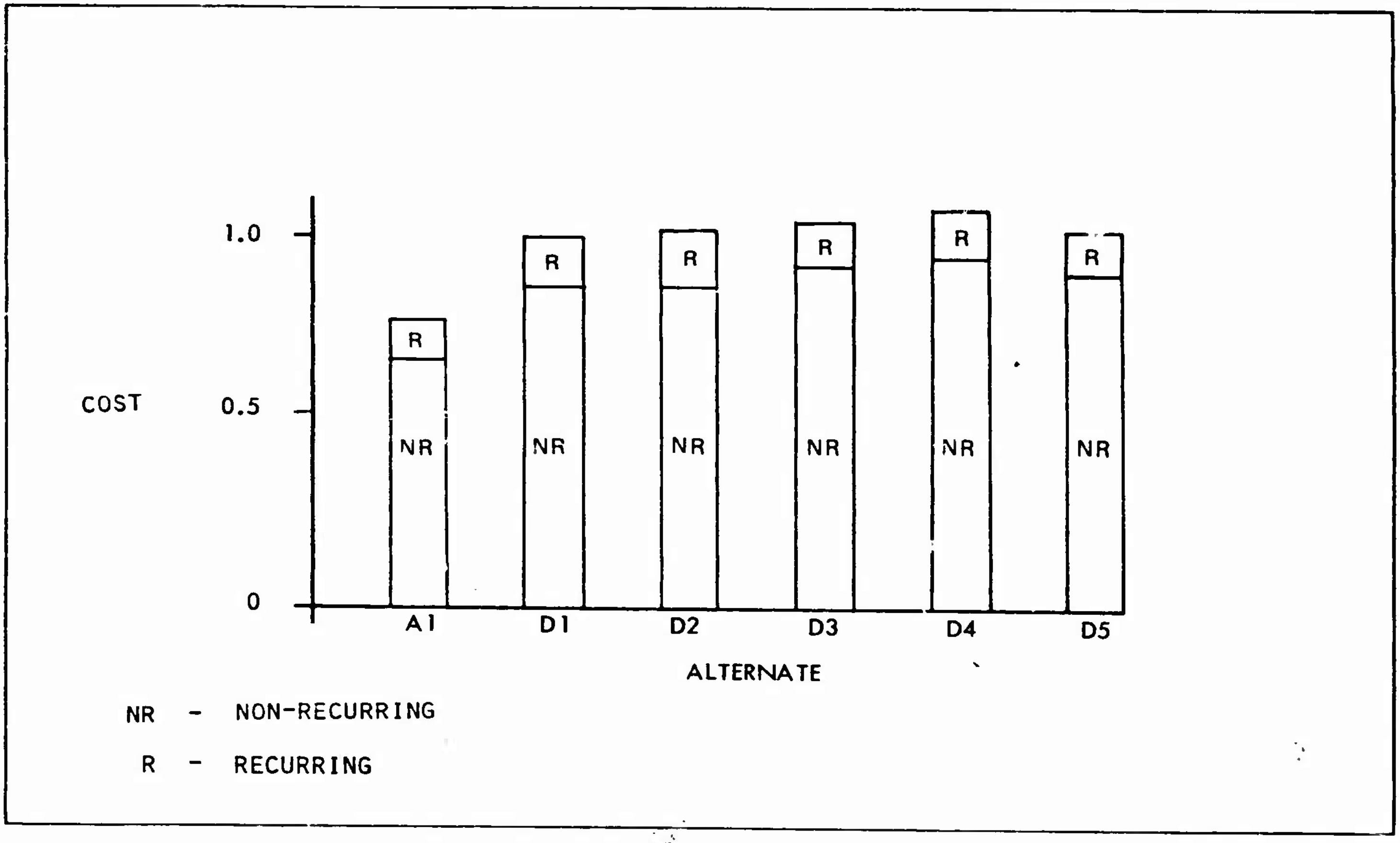


FIGURE 5-41 CONTROL SEGMENT COSTS - PHASE I

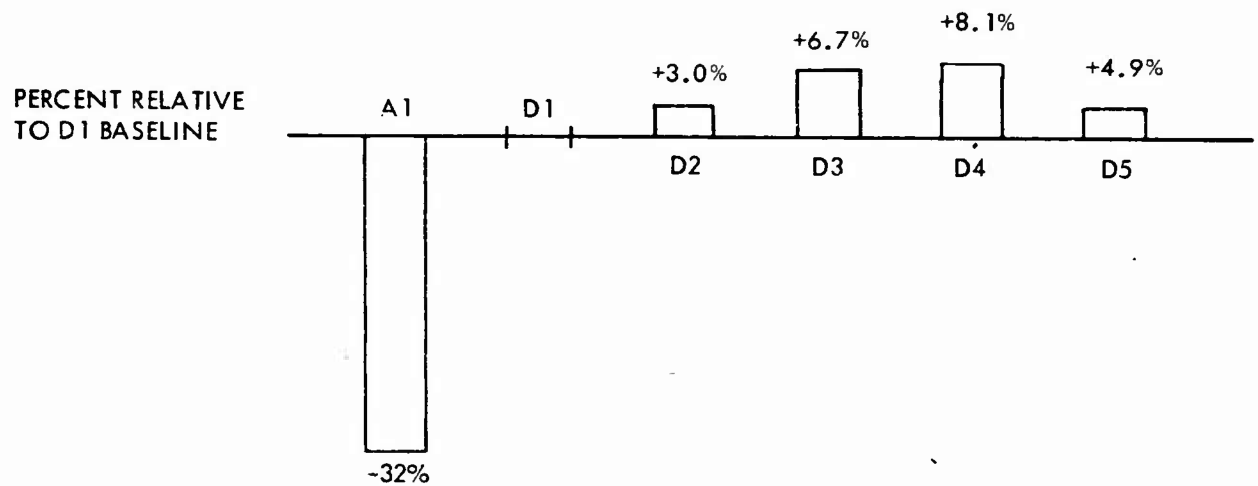


FIGURE 5-42 RELATIVE COSTS CONTROL SEGMENT - PHASE I

- ADD SECOND 4-CHANNEL RECEIVER TO ALL MONITOR STATIONS
- INTEGRATE AND TEST HW/SW FOR ADDED SATELLITES
- ADD 1/2 SHIFT FOR EXPANDED OPERATIONS SCHEDULE
- INCREASE UPDATE STATION TIME-ON-LINE
- RETAIN SCF BACKUP FOR T&C

FIGURE 5-43 UPGRADE FOR PHASE II

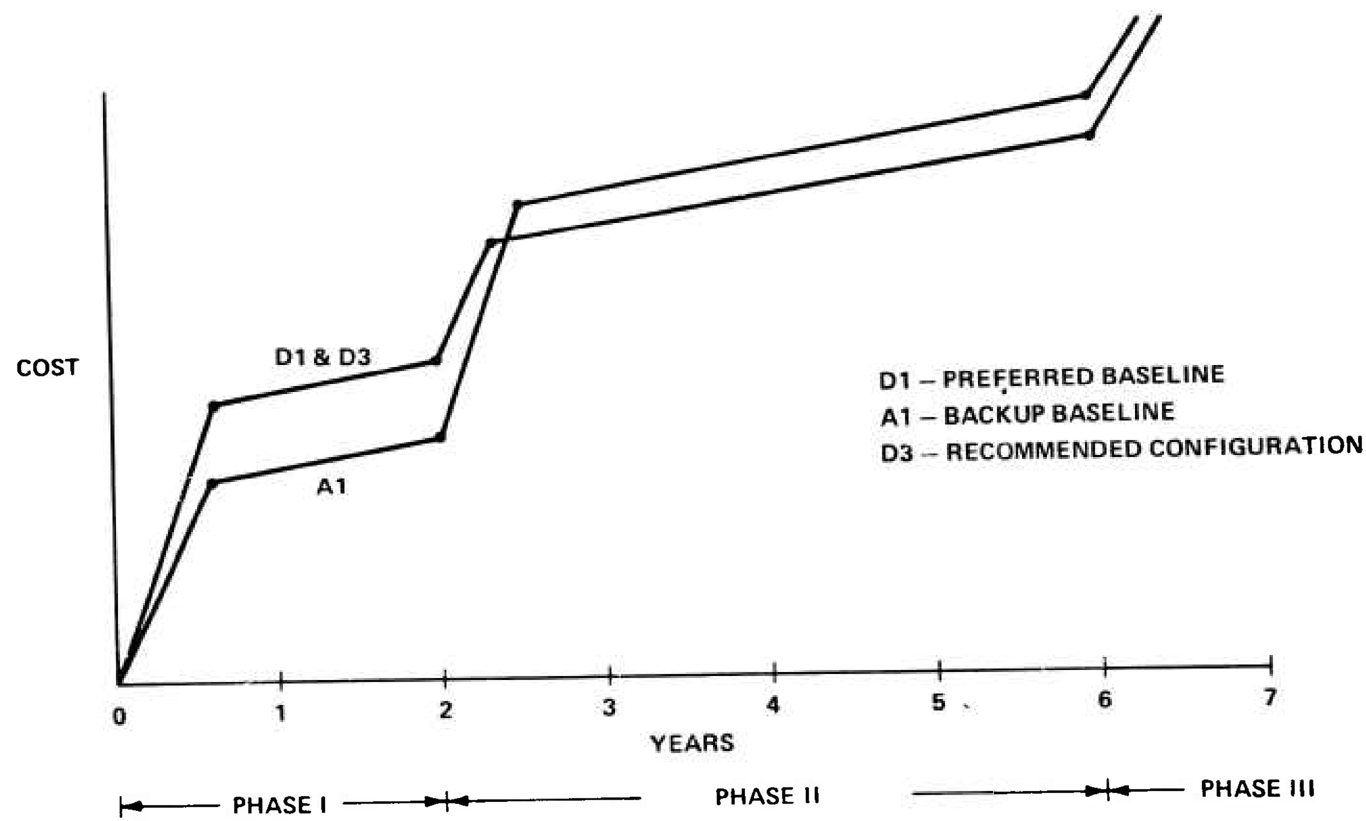


FIGURE 5-44 CONTROL SEGMENT COST THRU PHASE II

- REPLACE MONITOR RECEIVERS WITH 3 PRODUCTION MODELS PER SITE
- ADD REDUNDANT MCS DATA PROCESSING SYSTEM
- ADD REDUNDANT UPDATE STATION
- RETAIN SCF BACKUP FOR T&C
- INCREASE PERSONNEL TO SUPPORT 4 SHIFTS, 24 HOUR OPERATOR

FIGURE 5-45 UPGRADE FOR PHASE III

CONCLUSIONS

- A1 GIVES LOWEST INITIAL COST, LOWEST LEGACY
- D1 PROVIDES REASONABLE COMPROMISE
- D3 GIVES BEST LEGACY, HIGHEST INITIAL COST

FIGURE 5-46 CONCLUSIONS

6.0 Existing Facilities

This section is a compilation of Trip Reports to the various facilities. Reports and data which refer to NAG, SAC, NWL, and ELM are contained in Sections 1.6.1, 1.6.2, 1.6.3, and 1.6.4, respectively.

6.1 NAG

The following data refers to existing NAG facilities.

PHILCO

Intra Company

21 January 1974

TO: Distribution

FROM: J. M. Thornton

SUBJECT: NNSS Manpower information received from NAG, Point Mugu

REFERENCE: Trip Report, Naval Astronautics Group, Point Mugu NAS

As stated in the referenced trip report, arrangements were made on 15 January for NAG manpower management personnel to reproduce and send to the undersigned certain manpower-related information. This memo acknowledges the receipt of this information.

The following information was received on this date:

NAG Operations Dept Watchbills for December and/or January
NAG Organization Charts (positions and relationships)
NAG Organization Charts (functional statements)
Personnel Job Description and Duty Assignment sheets for the following Laguna Peak positions:

Watch Supv Operator/Technician
Section Leader
Station Operator/Technician
Operator Trainee
Operator/Technician Trainee
Watch Supervisor Station Operator
Supervisory Electronic Technician GS-856-12
Electronic Technician GS-856-11 to GS-856-04 (8 descriptions)

This information will be placed in the GPS file with copies held by the undersigned and also by those so designated on the distribution list.

James M. Thornton

James M. Thornton

GPS Distribution
(Original to Shaparenko file)
S. E. Carroll
M. E. Deggeller (w/encl)
R. N. Haislet
D. G. Middlebrook
H. H. Stern (w/encl)
D. E. Westby

PHILCO

Intra Company

21 January 1974

In Reference Cite:
3S7230-74-3

TO: J. T. Witherspoon

FROM: H. H. Stern

SUBJECT: Trip Report, NAG, Pt. Mugu NAS

Don Westby, Jim Thornton, Stan Carroll, and I visited the Naval Astronautis Group (NAG) Headquarters facility at Pt. Mugu NAS on January 14 and 15 1974. On January 15 we also visited the Laguna Peak facility.

The purpose of my visit was to observer Control Center and Injection/Monitoring operations in support of the Navy's TRANSIT Program. Principle contacts were with:

T. Smith	Systems
J. Pedersek	Vehicle Systems
C. Clark	Telecommunications
E. Ellis	Senior Satellite Controller
L Cdr G. Watson	OIC, Laguna Peak

Some salient observations:

1. Based on TRANSIT operations (six satellites, each uploaded twice daily), the control of GPS operations should be easily accomplished by one Controller, working one shift, especially during Phase I.

2. TRANSIT operations Controllers appear to rely more on CRT displayed system status information than on the hard-wired wall displays. One reason for this is the present wall display's inability to show TRANSIT's growth from a four to a six satellite system.

3. One of the reasons for the high reliability of TRANSIT uploading (they call it injection) lies in the fact that the injection station has several potential injection opportunities per pass, and that station turn-around from one two-minute injection window to the next appears to be achieved simply and easily.

4. In response to my questions regarding the most frequent or typical injection anomalies, bit errors in navigation data verification were cited. In addition, timing problems were encountered during our observation of injection at Laguna Peak, necessitating the use of the next injection window.

Harold Stern

H. H. Stern
Human Engineering Section

PHILCO Ford

Intra Company

18 January 1974

TO: J. T. Witherspoon

FROM: J. M. Thornton

SUBJECT: Trip Report, Naval Astronautics Group, Point Mugu, NAS

The undersigned, along with Messrs S. E. Carroll, H. H. Stern, and D. E. Westby, visited the subject facility on January 14 and 15 to become more familiar with the Navy Navigational Satellite System (NNSS) and with the Transit Operational Network (TRANET). The undersigned's area of interest was manpower.

Because of the inter-relationship of manpower with the hardware and software systems and with the operations and maintenance concepts, useful information was gained from discussions with NAG personnel in each of these areas as well as from discussions with NAG manpower management personnel. The trip included a complete tour of the NNSS Control Center and Laguna Peak Station.

A routine injection pass was observed from the operations console of the control center; another injection pass was observed from the Laguna Peak Station. There were some timing problems experienced during the latter pass which enabled the undersigned to observe the Laguna Peak personnel under non-nominal conditions. In addition to information gained through discussion and observation, certain documents were received on loan, while other information is being reproduced and should be received at WDL by the 21st. Loaned documents included Standard Operating Procedures, Standard Maintenance Failure Printouts. Reproduced information will include organization charts, position titles/descriptions, and manpower scheduling/augmentation tables.

The result of the trip was a good overall picture of how the NNSS presently operates and to what extent the GPS can be integrated into existing facilities, hardware, operations/maintenance concepts, and technical/non-technical/administrative support.

James M. Thornton

James M. Thornton

JMT:tmw

cc: S. E. Carroll
M. E. Deggeller
R. N. Haislet
D. G. Middlebrook
H. H. Stern
D. E. Westby

PHILCO Ford

Intra Company

18 January 1974

TO: R. N. Bryan

FROM: D. E. Westby

SUBJECT: Trip Report -- Naval Astronatutics Group, NAS, Point Mugu, California

PERSONS CONTACTED: NAG Headquarters

Name	Dept.	Phone No.
Cdr. A. Thayer	Operations Officer	982-8016
Lt. Cdr. Jack Klass	Planning Officer	982-8827
M. Moldenhauer	Manpower Management	982-8016
J. Podorsek	Operations	982-8016
G. Kennedy	Operations Computer	982-8702
C. Clark	Facilities Mgr.	982-8067
H. Kelly	Logistics SPM10	982-8067
J. Dell Amico	Hd. Eng. Div. SPM21	982-8827

Laguna Peak

Lt. Cdr. George Watson

1. Purpose: Messrs. J. Thornton, Stan Carroll, H. Stern and the undersigned visited the subject facilities on 14 and 15 January 1974 for the purpose of obtaining information regarding the location of GPS Master Control Station and Monitor Stations within the various Naval Astronautics Group facilities.

2. Details: Commander Thayer met with us and assigned responsible NAG personnel to provide requested information. After a general briefing session, we separated to various areas and went about obtaining desired data.

3. Facilities: Prior to leaving WDL it was determined that space for a total of 13 standard 19-inch racks would be required for the Master Control Station. The total of 13, included 2 racks for the Monitor Station function which is also to be located at Point Mugu. Space for additional monitor stations was to be determined for installation in Hawaii, Maine and Alaska.

3.1 Configurations: The NAG Facilities Manager, Charles Clark, advised that over 300 square feet could be made available in the Communications Area of the headquarters building. This provides adequate space for the 11 racks of the Master Control Station; however, the two racks for

the monitoring function would be located in an adjacent building. Since the monitoring function does not require manning, this arrangement was considered satisfactory.

The adjacent location is presently planned as the NAG Ready Test Facility, and will be the location of a PDP 11/40 Computer, primarily to be for software development.

NOTE: It has since been determined that the 2 racks of timing equipment will be located at the update station, Elmendorf, Alaska, in lieu of the MCS, and accordingly, the two racks for the monitor function can be located in the present communications area.

3.2.3 Electric Power: Adequate electric power is available from the NAG existing plant. The local Electrical Utility Company provides service to a motor-generator set, which can output a total of 250 kw, 3 phase, 120/208 volts, 60 Hertz electric power. The m-g set is coupled to an emergency diesel engine through a magnetic clutch. A 3-ton flywheel provides smoothing of transient conditions. Present peak loads for the system is approximately 150 kw. Accordingly, our present estimated maximum of 50 kw can be readily handled. All the remote sites are similarly powered and have ample capacity to meet the requirements of the Monitor Station racks.

3.3 Air Conditioning: The NAG Facility at Point Mugu has a separate AC plant, consisting of two 120-ton units. Present requirements have never exceeded the capacity of a single unit, and consequently, the second unit is utilized as a back-up. All the remote sites are similarly equipped with ample capacity.

3.4 Fire Protection: All NAG buildings are provided with suitable fire protection devices. Carbon dioxide is available under the false flooring and for wall units. Sprinkler systems (dry pipe) are available in office areas, etc.

3.5 Logistics Facilities: The NAG Logistics Department provides all their present support for the remote sites, in addition to the headquarters. No problems could be determined for providing the additional support needed for GPS.

3.6 Grounding Facilities: All equipments, buildings, etc. are brought to a common ground 10-point grid located adjacent to the main NAG building. No special attention has been required to keep the proper resistance level for the system. All remote sites are similarly grounded, but one or two require occasional chemical enhancement of the surrounding earth, in order to maintain proper resistivity. Note that only one ground point is used for all equipments, which may cause some red/black interface problem.

4. Documents: The NAG personnel were very accommodating in providing any documents we wished regarding the Hq and the remote sites. Documents brought back included the following:

   a. Configuration Baseline Directive

      1. Plot plans of sites

      2. Building plans

      3. Room plans showing existing equipment arrangements

      4. Equipment lists and rack elevations

      5. Function flow diagrams

   b. Maintenance Instructions/Procedures

5. Communications Facilities: The following information regarding communications facilities was obtained from the NAG representatives:

   a. Lines would be available between Hawaii and Pt. Mugu, and Maine and Pt. Mugu for 10 minutes once each hour (800 kbits per day and 32 kbits once per hour).

   b. Multiplexer could be added, if desired.

   c. Modems can be added in the Comm area.

   d. No problem in adding cables for the MCS.

   e. Cable capacity is available on not-to-interfere basis for 10 minutes each hour between Pt. Mugu and Laguna Peak facilities.

D. E. Westby

cc: J. Carroll
S. Carroll
S. Crawford
R. Crum
K. Hornberg
D. Middlebrook
H. Stern
J. Thornton
J. Witherspoon

PHILCO Ford

Intra Company

16 January 1974

TO: J. E. Theibault

FROM: S. E. Carroll

SUBJECT: Trip Report, Naval Astronautics Group, Point Mugu, NAS

On January 14 and 15, I visited the NAG group for the purpose of familiarization with their software systems. Principle conversations were held with Gary Kennedy (software), and Tom Smith (satellite). On Tuesday the 15th, we were shown the Laguna Peak Tracking Station by Lt. Cmdr. Watson.

Many of our questions were answered by a viewgraph presentation and an appendix to a systems analysis report prepared by NAG group (attachments 1 and 2).

The NAG group was most helpful, and seem interested in supporting the GPS program in anyway possible. However, they do feel that any such support should be integrated with their system, rather than using parts of it, i.e., the data lines. It would also appear that time will be available on the PDP 11/40's at the remote sites and perhaps on the 360/40 at the headquarters facility. There is currently no computer interface between NAG and the NWL or SCF. The stations are to be upgraded beginning 5/76 (Maine) and terminating 9/77 (Hawaii). There will be at Pt. Mugu, a test site for software development. It is my impression that this will be a permanent facility and available as a development facility to outside users.

S E Carroll

S. E. Carroll

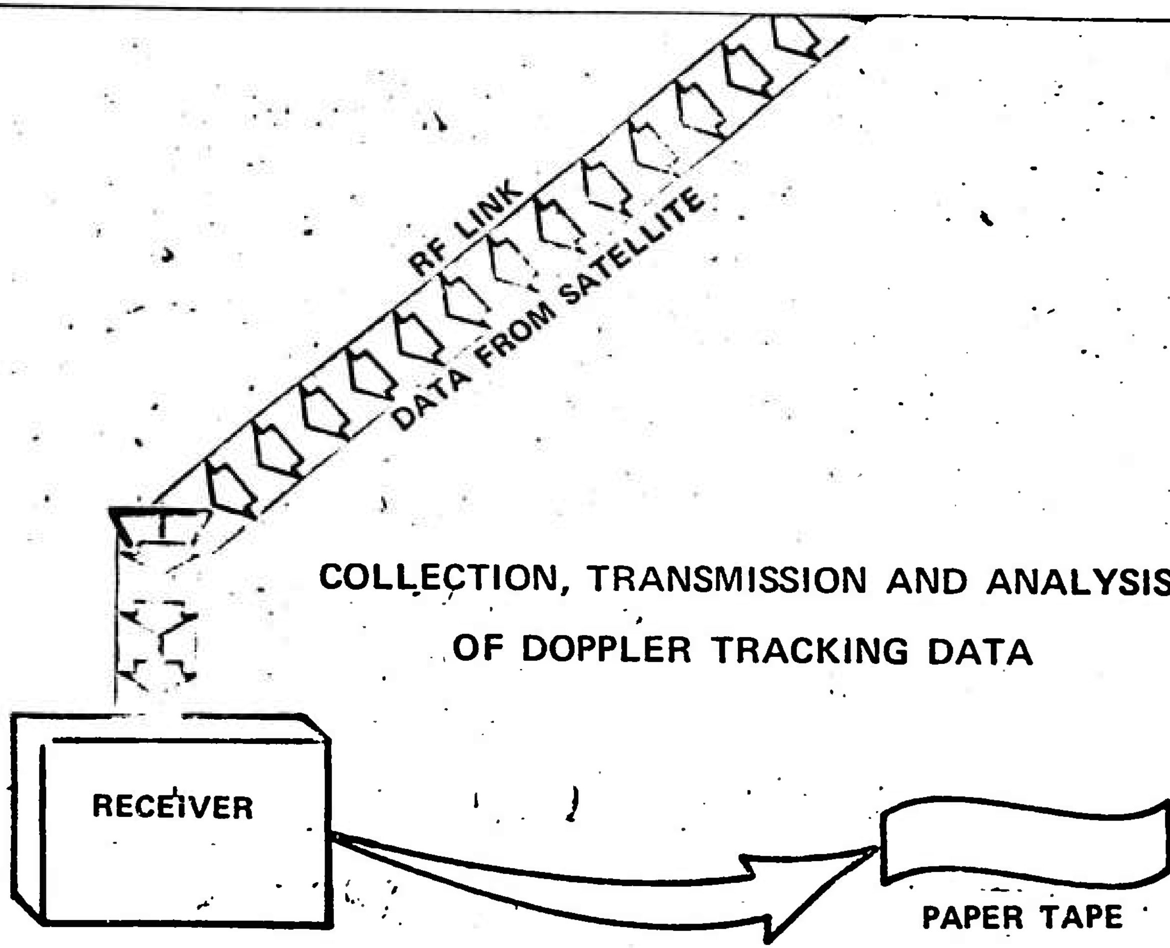
SEC:pb

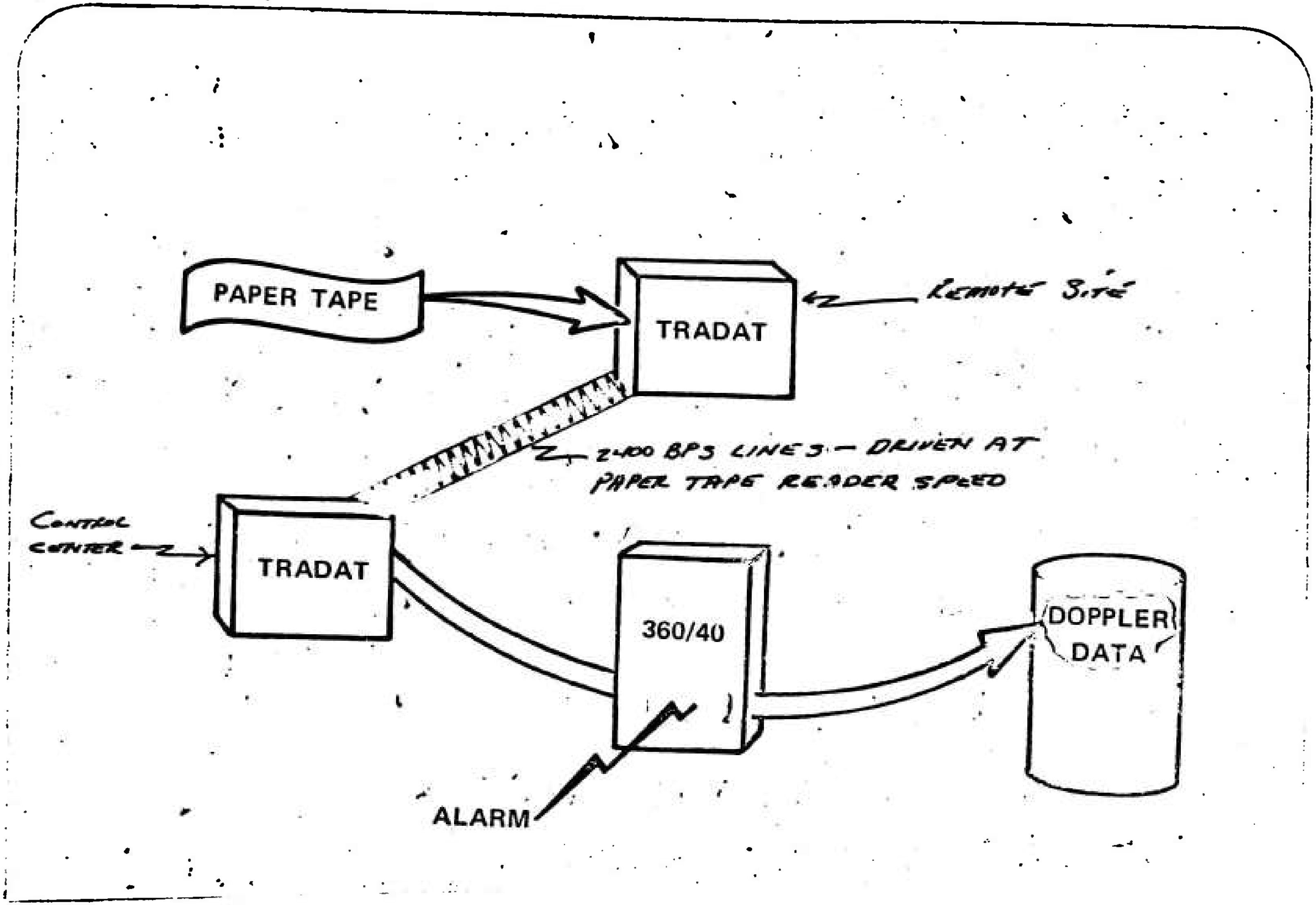
cc: D. R. Potter
O. C. Holzborn

attach.

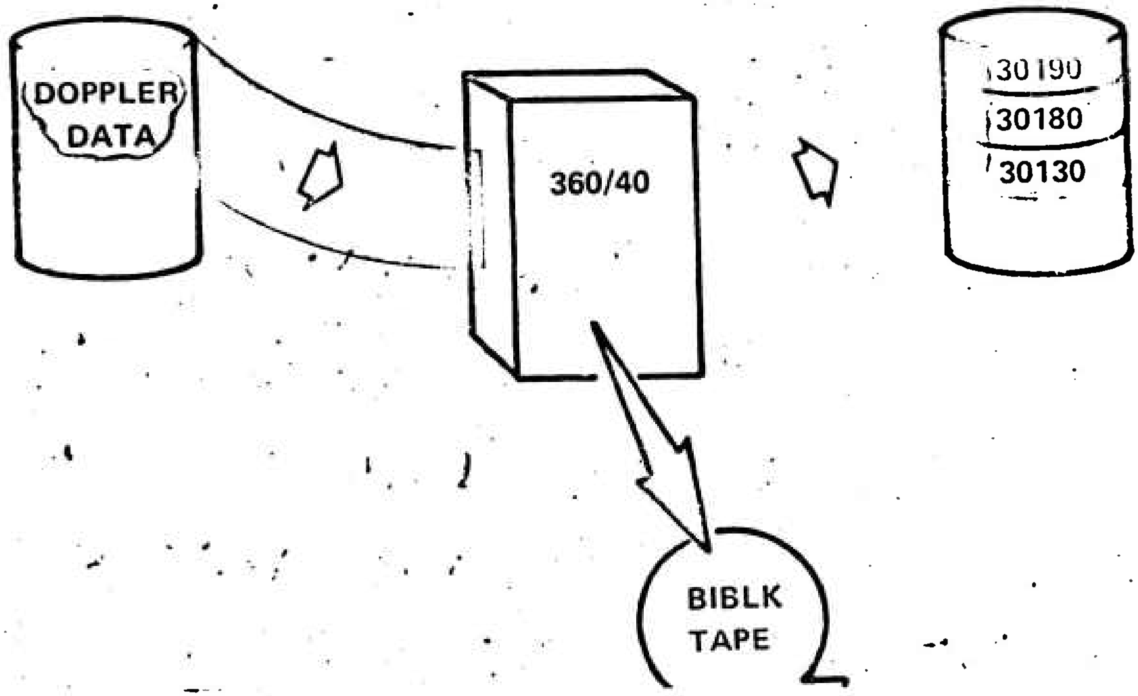
COMPUTATIONAL FLOW OF NNSS DATA

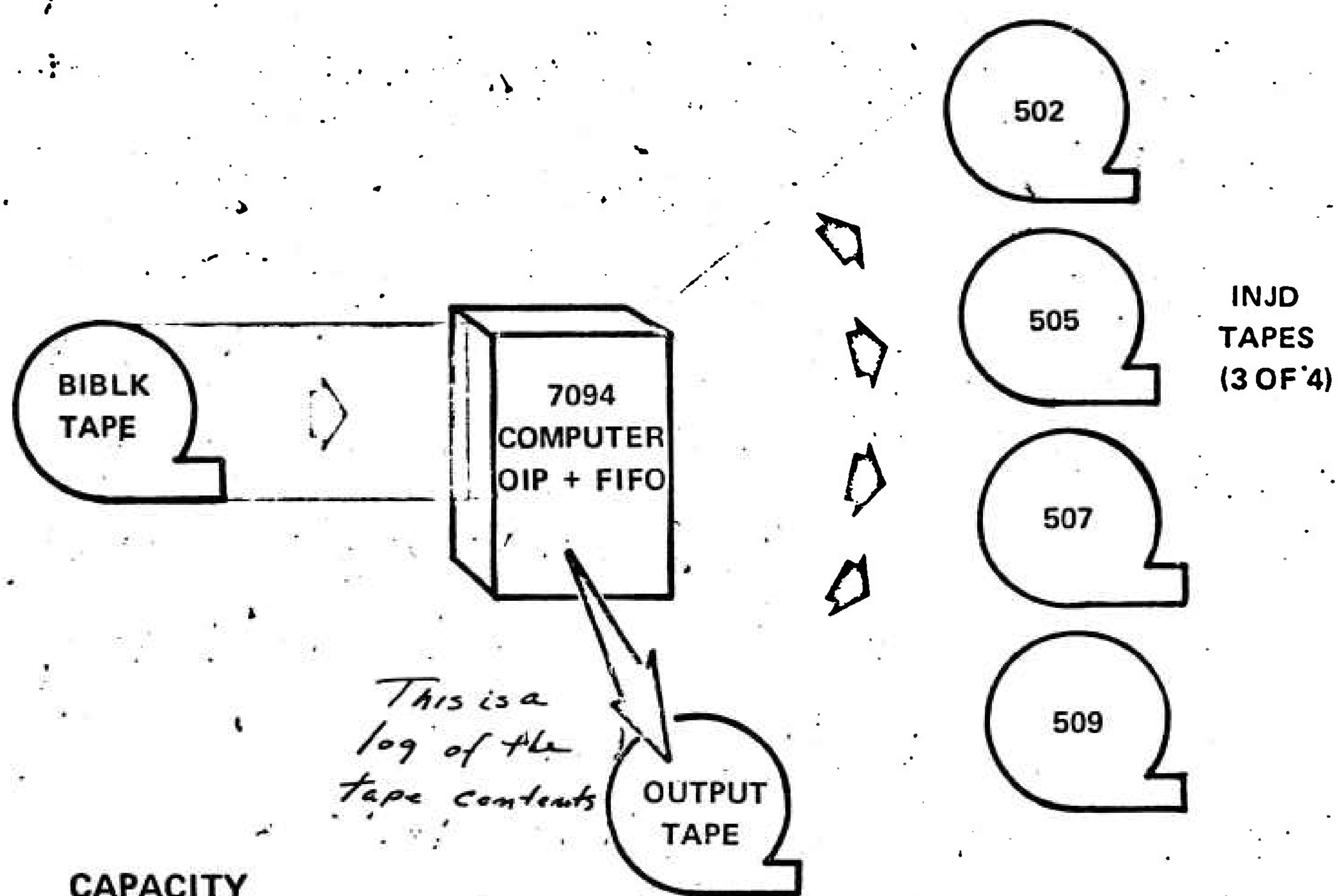
COLLECTION, TRANSMISSION AND ANALYSIS OF DOPPLER TRACKING DATA




PAPER TAPE
TRADAT
REMOTE SITE
2400 BPS LINES — DRIVEN AT PAPER TAPE READER SPEED
CONTROL CENTER
TRADAT
360/40
DOPPLER DATA
ALARM

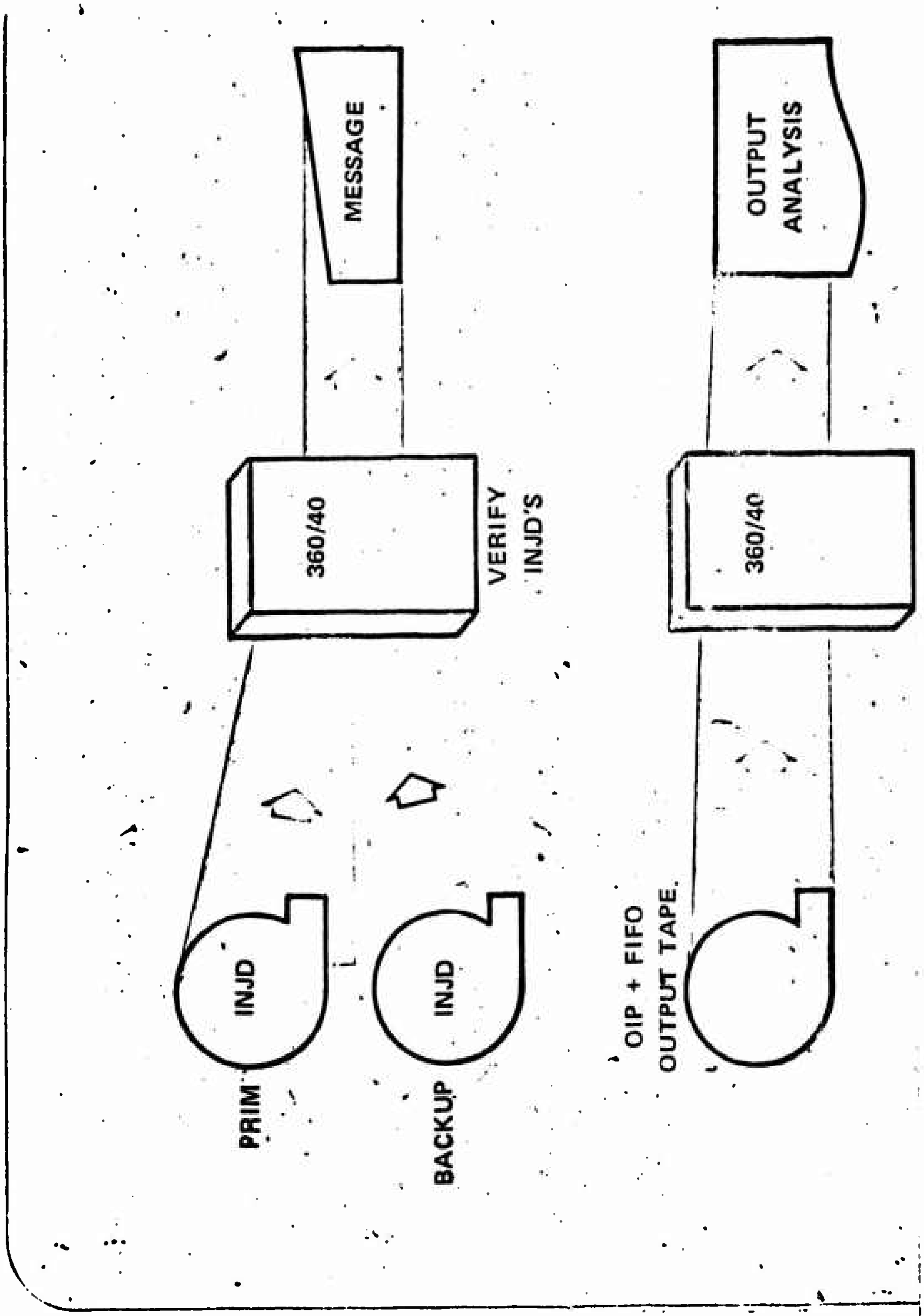
COMPUTATION OF UPDATED SATELLITE MESSAGE AT HEADQUARTERS



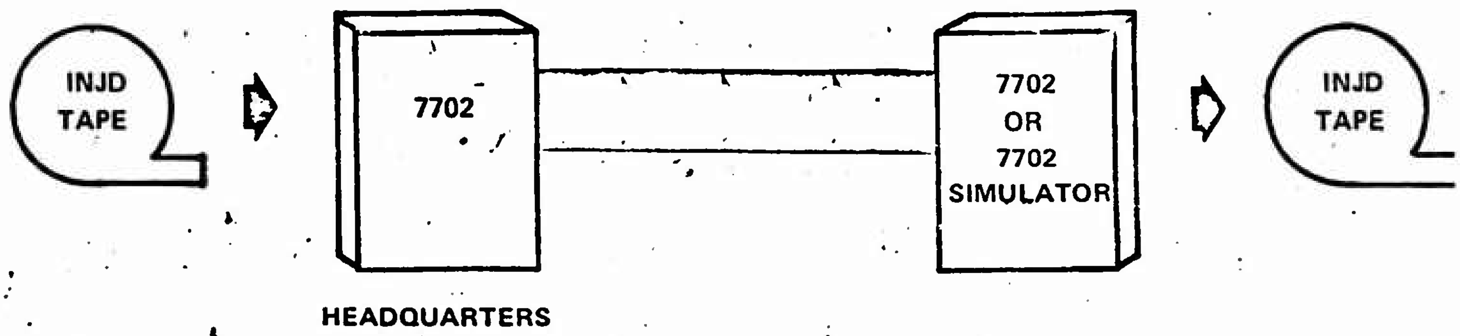


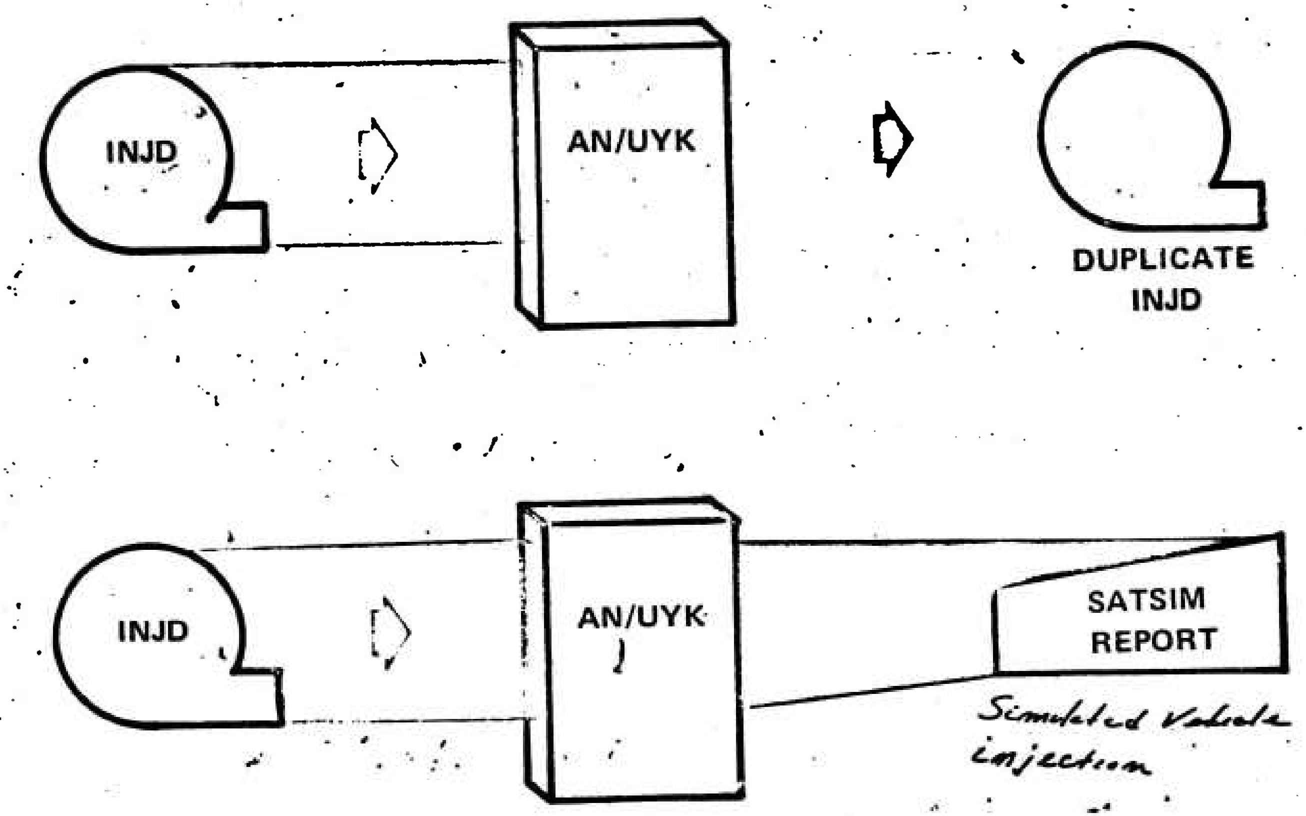
BIBLK TAPE
7094 COMPUTER OIP + FIFO
502
505
507
509
INJD TAPES (3 OF 4)
OUTPUT TAPE
This is a log of the tape contents

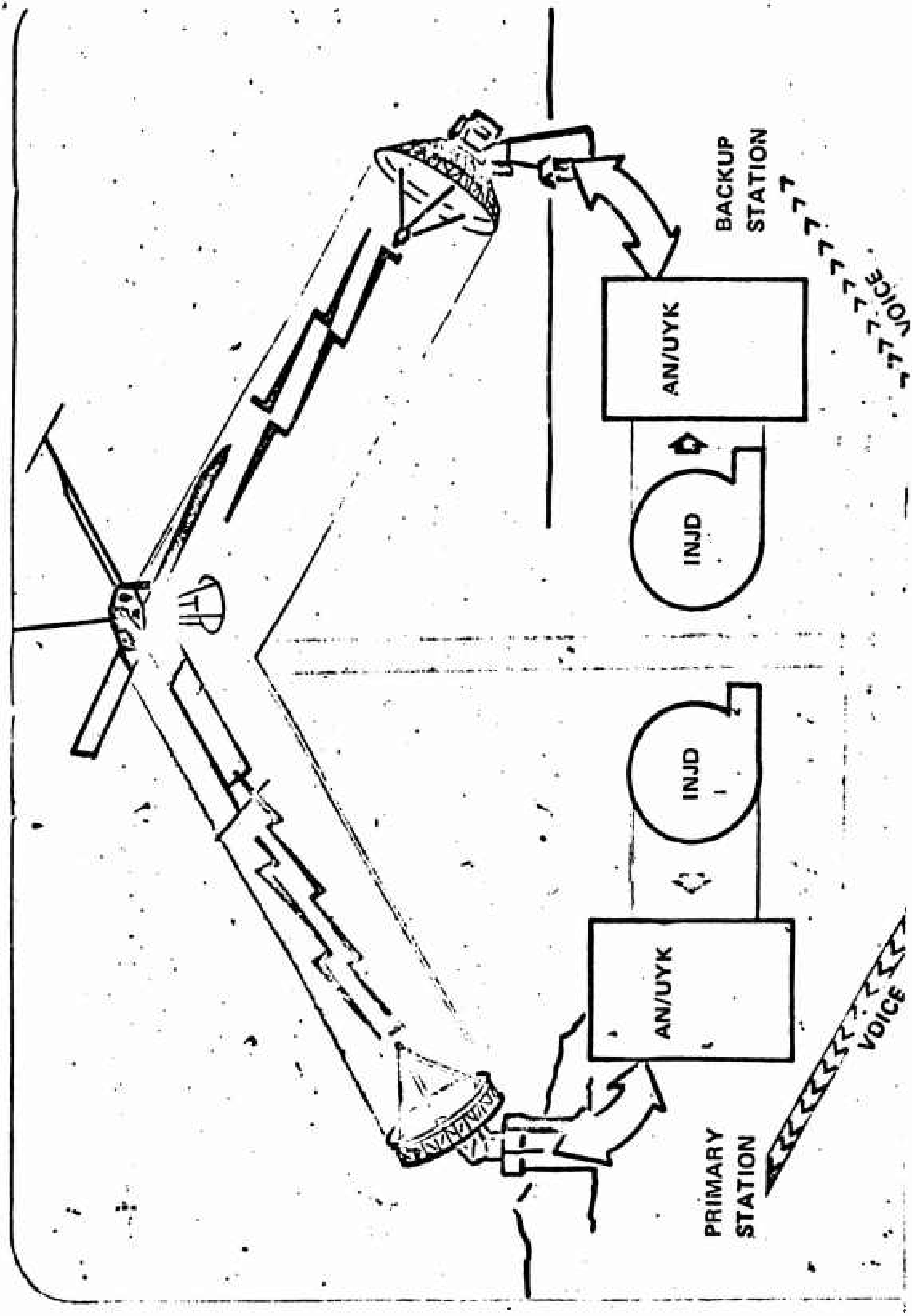
CAPACITY


MESSAGE
OUTPUT ANALYSIS
360/40
VERIFY INJD'S
360/40
INJD
PRIM
INJD
BACKUP
OIP + FIFO OUTPUT TAPE.

TRANSMISSION AND INJECTION OF UPDATED MESSAGE



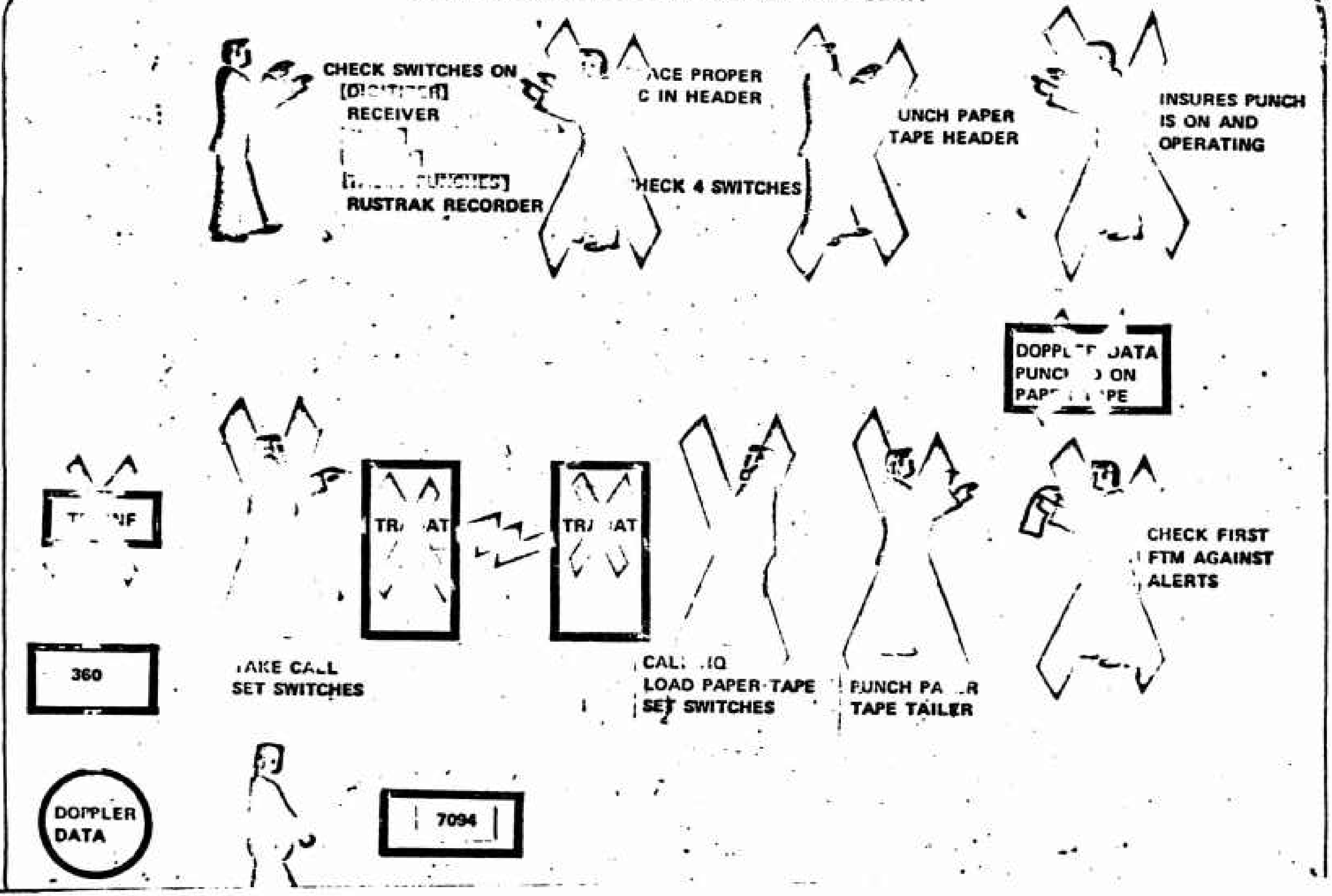

INJD
AN/UYK
DUPLICATE INJD
INJD
AN/UYK
SATSIM REPORT
Simulated Vehicle injection

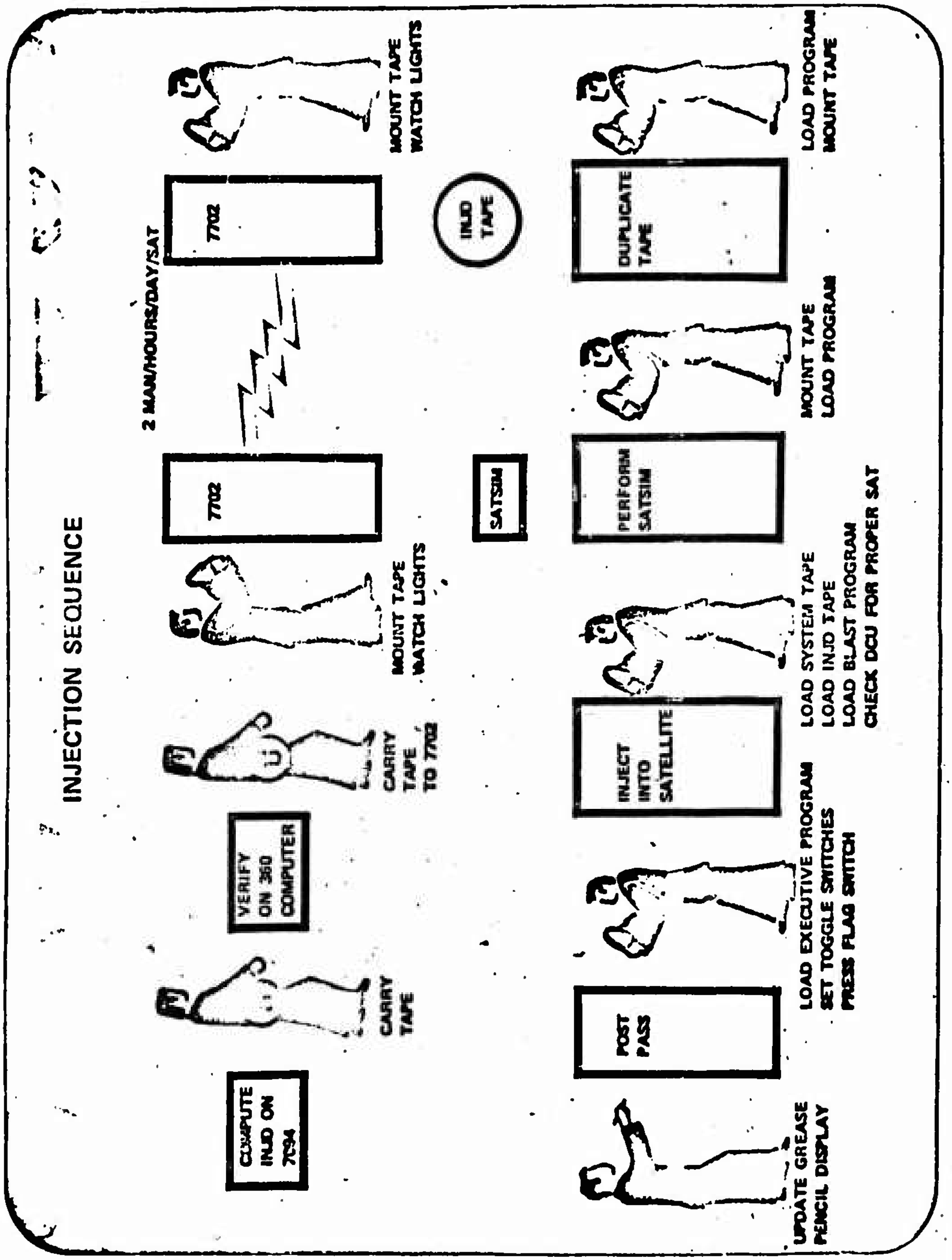


PRIMARY STATION
VOICE
AN/UYK
INJD
INJD
AN/UYK
BACKUP STATION
VOICE

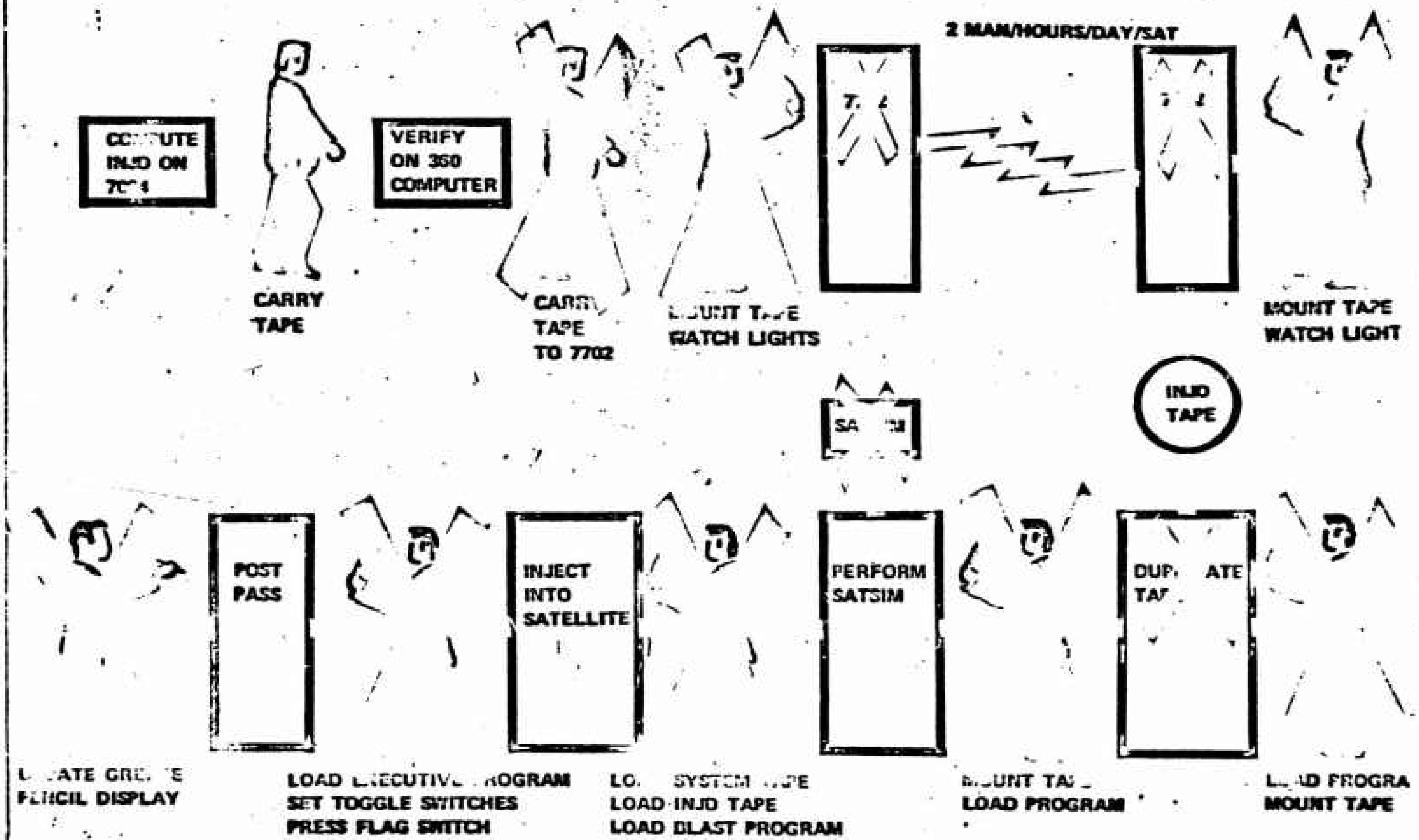
Xed out and blocked out functions indicate upgraded system

COLLECTION OF DOPPLER AND MEMORY DATA

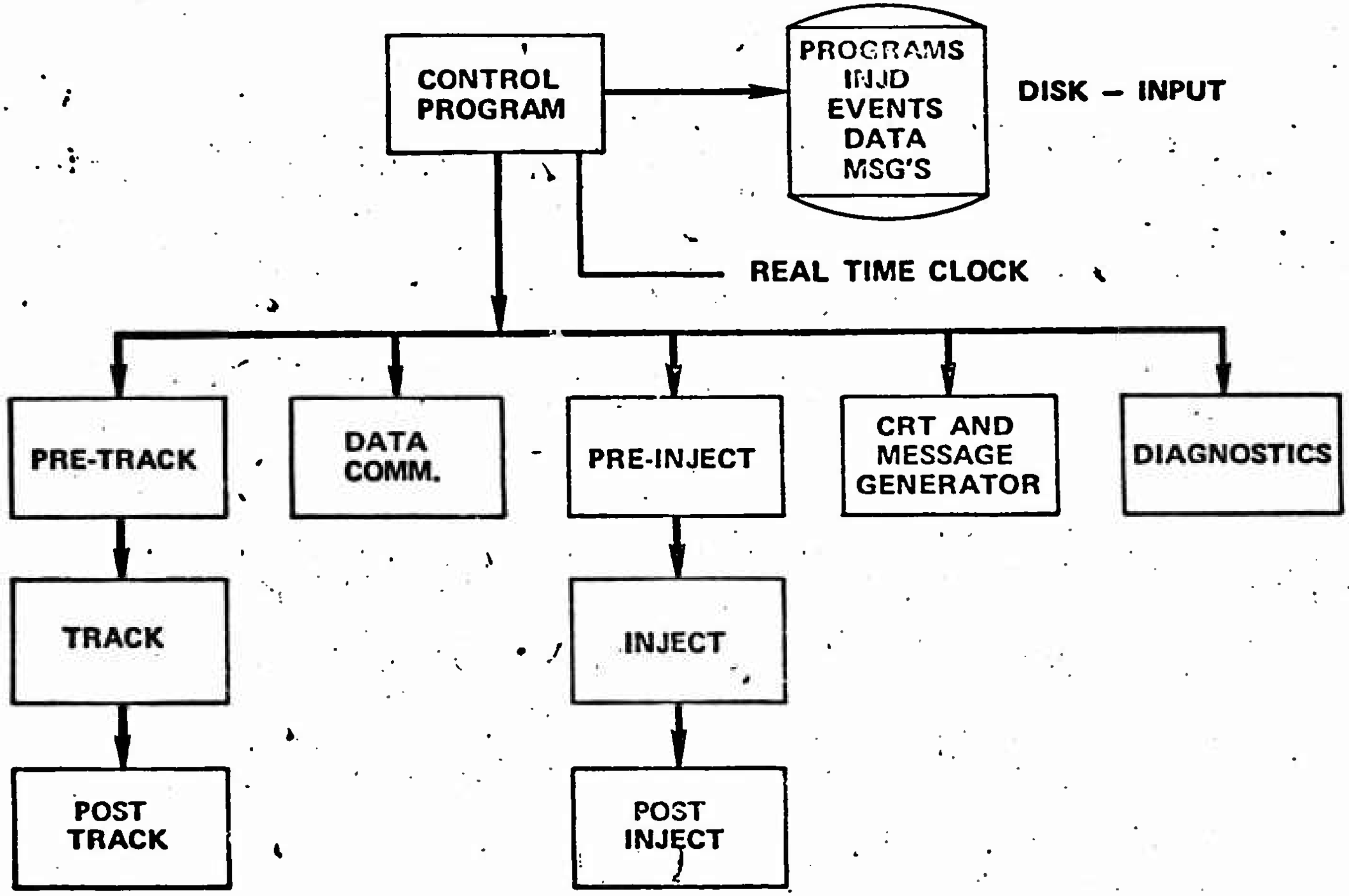



INJECTION SEQUENCE
COMPUTE INJD ON 7094
CARRY TAPE
VERIFY ON 360 COMPUTER
CARRY TAPE TO 7702
MOUNT TAPE WATCH LIGHTS
7702
2 MAN/HOURS/DAY/SAT
7702
MOUNT TAPE WATCH LIGHTS
SATSIM
INJD TAPE
UPDATE GREASE PENCIL DISPLAY
POST PASS
LOAD EXECUTIVE PROGRAM
SET TOGGLE SWITCHES
PRESS FLAG SWITCH
INJECT INTO SATELLITE
LOAD SYSTEM TAPE
LOAD INJD TAPE
LOAD BLAST PROGRAM
CHECK DCU FOR PROPER SAT
PERFORM SATSIM
MOUNT TAPE
LOAD PROGRAM
DUPLICATE TAPE
LOAD PROGRAM
MOUNT TAPE

INJECTION SEQUENCE



GENERAL SOFTWARE FLOW



Appendix A

Basic System Operation

1. This section of the report will provide a general description and define the general function of how the proposed ground system would work with the new station computer. The updated ground system would allow outdated and obsolete hardware to be replaced by the new station computer and associated software. The system upgrade would be accomplished by replacing the AN/UYK computer and specially designed obsolete station equipment with a general purpose computer with a limited amount of highly reliable input/output equipment. A generalized diagram of the major components of the proposed ground station configuration is shown in figure 1-A. A list of the equipment that could be deleted is shown in table 1-A.

2. With the more powerful general purpose computer the basic station functions would be performed as follows:

a. Central Control with Local Override.

Under the proposed system the Detachment will be operating from a schedule generated by the NAVASTROGRU IBM 360 control system schedule program. This will ensure that the schedule used for operations at the Detachment are identical to the master control schedule used by the NAVASTROGRU Duty Satellite Controller (DSC) at the Headquarters Control Center. This schedule will be computed automatically, taking into account inoperative equipment and various conflict situations. Generation of this schedule is currently performed at a minimum of once a day but can be run more frequently if requested by the DSC. Once a schedule is created, the schedule of orders unique to an individual Detachment will be transmitted to that Detachment. This schedule will allow the Detachment computer to initiate functions according to the same schedule in use at Headquarters. This type of system will also allow the computer to display future orders for the Detachment on the automated display, replacing the current manual grease pencil display. The orders generated by the schedule program will consist of the following items and associated times.

(1) Take doppler.

(2) Auxiliary commands.

(3) Inject and type of injection.

(4) Memory compare.

(5) Perform navigation.

(6) Take telemetry.

Hard copies of the generated orders will be available for the DSC and the Detachment operator. The orders could be overridden by the DSC at Headquarters or by the Detachment operator. The DSC at Headquarters will be notified on his CRT if the Detachment overrides any orders.

This part of the system upgrade is relatively simple to accomplish as the schedule proposed for use is currently computed by the IBM 360 at Headquarters for use by the DSC. Creation of a software routine to transfer data from the IBM 360 to the Detachment computer completes the requirements. No specially engineered hardware will be required. This area of improvement provides the following advantages to the system.

(1) Central control and computer agreement between Headquarters and the Detachments' orders.

(2) Capability of the Detachment computer to initiate action without human intervention.

(3) Replacement of a manual display at the Detachment with an automated display reduces the possibility of human error.

If, for some reason, Headquarters could not transmit orders to the Detachment, the Detachment operator will have the capability to input orders from a long-range schedule which he will continue to receive under the proposed system. Once these orders were entered, all other functions will operate as stated above.

b. Provide Headquarters Monitoring of the Detachment.

The Headquarters computer will auto-dial the Detachment computer to ensure that scheduled events were in progress when scheduled. If the Headquarters computer failed to get a notification that a scheduled event was in progress the DSC will be flashed a warning alarm in the Control Center. This feature is recommended because it can be implemented with minimal software and no special hardware and will provide an automated check in the system.

c. Satellite Memory and Doppler Data Collection and Monitoring.

The upgraded ground system will have the capability to collect satellite memory data on all tracking passes. The memory data will be stored on disk by the Detachment computer. The station computer will have the capability of performing a memory compare. If there are errors the intervals that are in error will be transmitted to Headquarters. These results will then be displayed on the CRT at Headquarters and stored on disk for possible later retrieval. The DSC at Headquarters will have the capability to obtain the entire memory pass of data when required.

The doppler data recovery will be performed at the Detachment by using the new station computer and an associated interface to the receiver. The doppler data will be read into the station computer and a timing error computed and displayed; the doppler data will be formatted and stored on disk. Following a request from the Headquarters computer, the data will be read from disk and transmitted to the Headquarters computer. The Headquarters 360 will then perform a navigation, timing analysis and pass analysis check on the pass. If the result of the check exceeded a

threshold, the DSC will be notified of error. The navigation and timing errors for all passes will be stored on disk at Headquarters for possible later retrieval. This method of handling doppler and memory data provides the following advantages.

(1) Eliminates the need for the following special purpose equipment in the doppler and memory collection area.

(a) Satellite Memory Simulator.

(b) Time Recovery and Memory Readout Units.

(c) Header/Tailer Hardware and Tally Punches.

(d) TRADATS at the Detachment and Headquarters.

(e) TRAINF at Headquarters.

(2) Eliminates paper tape and the associated problems for doppler and memory recovery.

(3) Provides for the capability of automated data transmission.

(4) Eliminates a number of manual human intervention steps.

d. <u>Injection Control and Auxiliary Commands.</u>

The updated ground system will be capable of performing all types of injections and auxiliary commands that are performed in the current ground system. The injections will be controlled from the Detachment computer using the injection data (INJD) tape which was sent from Headquarters and stored on disk at the Detachment. The actual injection sequence will be identical to the manner in which it is currently performed with the new station computer performing the functions that are currently performed by the AN/UYK. The more powerful station computer provides expanded capability and will facilitate the upgrading and replacement of hardware components in the injection and auxiliary command system when changes were required or deemed desirable in these areas. In addition, the new station computer with its additional core and faster internal speed will allow for more computer capabilities during the actual injection.

e. <u>Message Generation.</u>

With the updated ground system the message generation will be done with the use of a CRT versus the current method of using the teletype and associated paper tape system. The Detachment or Headquarters personnel will type their message on a CRT and have the capability of making any required corrections. Once the body of the message was thought to be correct a key would be depressed

and the message formatted and stored on disk as well as printed on hard copy. The operator will then take the hard copy of the message to have it verified by his supervisor. If the message is correct a code will be entered allowing the message to be released. If a change was later desired, the message could be called back to the CRT and the change could be made. The message generation system of the updated system will have the following advantages over the current system.

(1) Eliminate the teletype for normal message generation.

(2) Eliminate paper tape and its associated problems.

(3) Provide the capability to automate message transmission.

(4) Provide for faster message generation and better error correction capabilities.

Classified message generation will be performed in the same manner used in the current system.

f. Injection Data Tape Transmission.

With the updated ground system the INJD tapes will be hand carried to the IBM 360, where they will be verified for continuity and reasonableness using the old INJD data. If it was found to pass the above tests, it will be stored on the Headquarters disk and sent to the Detachments using an automated transmission system with extensive parity checks. The INJD tape will be stored on disk at the Detachment where it will be used for the SATSIM and injection. This method of transmitting the INJD tapes provides the following advantages over the current system.

(1) Allow the IBM 7702's to be released.

(2) Eliminate the need for operators to watch lights blink for two man hours/day/satellite.

(3) Significantly reduce the transmission time required for INJD tapes.

(4) Eliminate the requirement of the Detachment to duplicate the INJD tape.

g. Doppler, Memory, and Fixed Frequency Message Data Transmissi

In the current system the transmission of doppler, memory, fixed frequency and message data transmission is accomplished by an outdated paper tape system which uses specially built hardware with a significant amount of manual intervention required for successful transmission. Two and

sometimes three people are involved in every data transmission with the current system. With the proposed system this data transmission will be accomplished by an automated approach where the Headquarters computer automatically dials the Detachment computer to send and receive data to and from the Detachment computer. As message data is received at the Detachment or Headquarters, hard copies would be generated. Figure 2-A shows a flow diagram of the current and proposed updated method of handling doppler, memory, fixed frequency and message data transmission. The updated system provides the following advantages over the current system.

(1) Release of the TRADAT components at the Detachments and Headquarters.

(2) Release of TRAINF equipment at Headquarters.

(3) Eliminate use of paper tape and manual intervention for normal operations.

(4) Remove the requirement for two communication operators to be involved for the duration of every transmission.

(5) Transmission time of data would be greatly reduced since the speed of a paper tape reader will no longer be a restriction.

h. Telemetry Data Reduction.

Telemetry data for the OSCAR series of satellites will be handled the same way it is handled in the current system with the special telemetry equipment. The digital telemetry of the TRIAD satellite will be reduced in a similiar method used by APL/JHU in reducing the TRIAD satellite telemetry data on the SIGMA-3 computer.

i. Antenna Pointings.

With the initial updated system the antenna pointings will be calculated by the Detachment computer and the antennas pointed as they are now, each with its own controller; however, it is planned that the updated system will be expanded at a later time to have the Detachment computer both calculate and automatically control the pointing of the antennas thus eliminating the need for the current antenna controller systems.

j. Backup Considerations for Essential Data Transmission.

With the proposed ground system the backup of Headquarters for the receipt of doppler and memory data and the transmission of INJD tapes will be performed by the Laguna Peak station as that station would have magnetic tape capability. In the current system Laguna Peak backs up Headquarters for these functions.

k. APL/JHU Data Transmission.

With the proposed ground system the data transmission to APL/JHU could be performed as in the current system of IBM 7702 to IBM 7702 for magnetic tape transmission and TRADAT to TRADAT for paper transmission or could be handled by transmission from NAVASTROGRU's computers to an APL/JHU computer. NAVASTROGRU recommends that the data transmission between NAVASTROGRU and APL/JHU be handled by transmission from NAVASTROGRU's IBM 360 and also from NAVASTROGRU's Laguna Peak ground station computer (in case the IBM 360 is down) to an APL/JHU computer, as the other solution would require that both NAVASTROGRU and APL/JHU retain an IBM 7702 and a TRADAT.

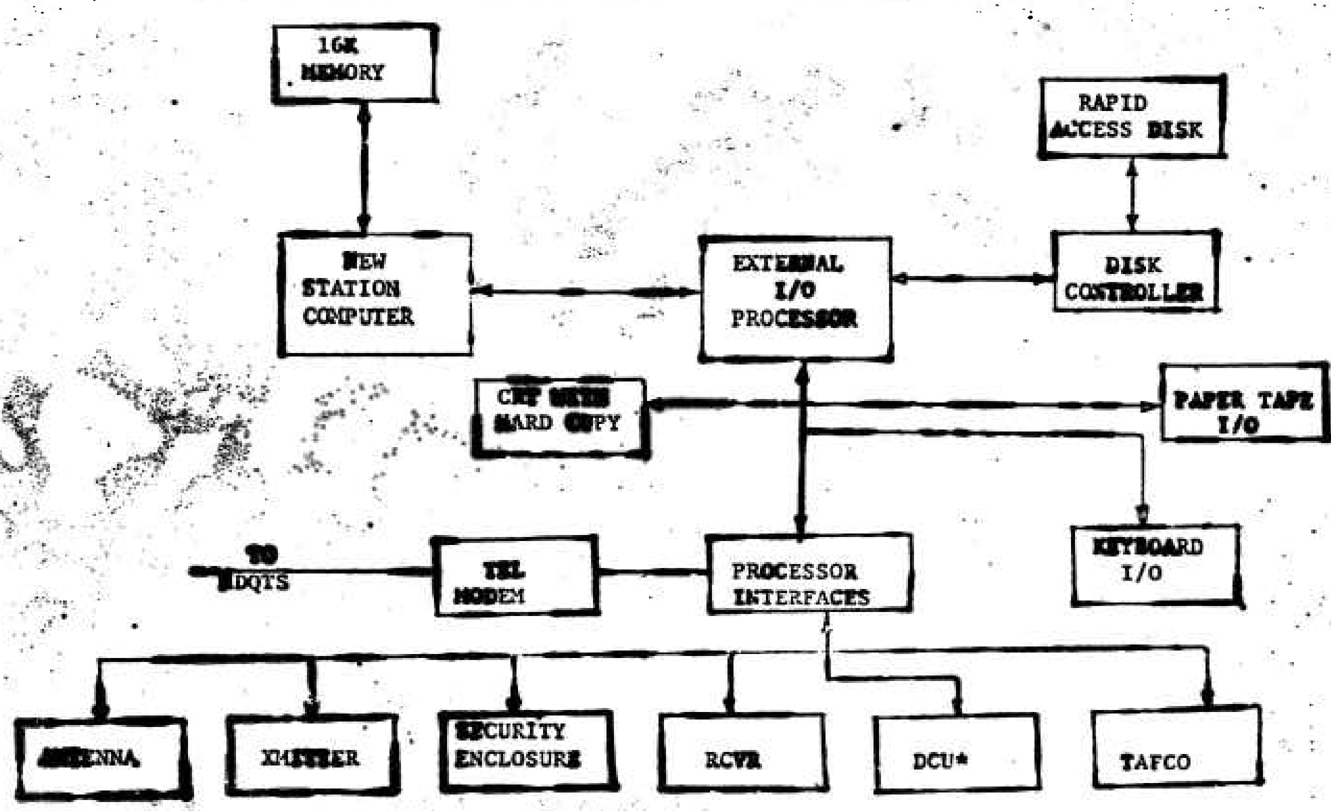
3. With the new station computer and the described method of station operation, black box type equipment will be eliminated in the doppler and memory collection and data communication areas. The new computer for the ground station would also have the capability to eliminate antenna controllers and telemetry black box equipment at a later date. In addition to eliminating the black box equipment and reducing the associated maintenance, training, and logistic requirements, the amount of mundane human intervention will be significantly reduced since a majority of the black box equipment being eliminated is paper tape handling equipment which requires excessive human intervention.

4. The proposed communication system does not rely on human intervention or involve paper tape. These factors coupled with faster transmission capabilities will greatly increase the communication potential of the NAVASTROGRU ground system as shown in table 2-A. In addition to providing the increased capability, the proposed communications system should result in a reduction in personnel required to handle the communications functions since most of the required functions have been automated.

5. With the additional speed, storage, and flexible I/O capabilities of the new computer, the ground stations will have the available computer power to integrate additional equipment as required. This, coupled with the automated communications and elimination of manually operated high maintenance equipment, will significantly increase the ground station capability and expansion potential.

Figure 1-A

MAJOR COMPONENTS OF PROPOSED GROUND STATION CONFIGURATION



*INITIAL CONCEPT IS PARTIAL AUTOMATION OF DCU FUNCTIONS PRIMARILY DISPLAY DATA AT OPERATOR CONSOLE

Figure 2-A

CURRENT SYSTEM

1. HANDLING OF DOPPLER, MEMORY, AND FIXED FREQUENCY DATA

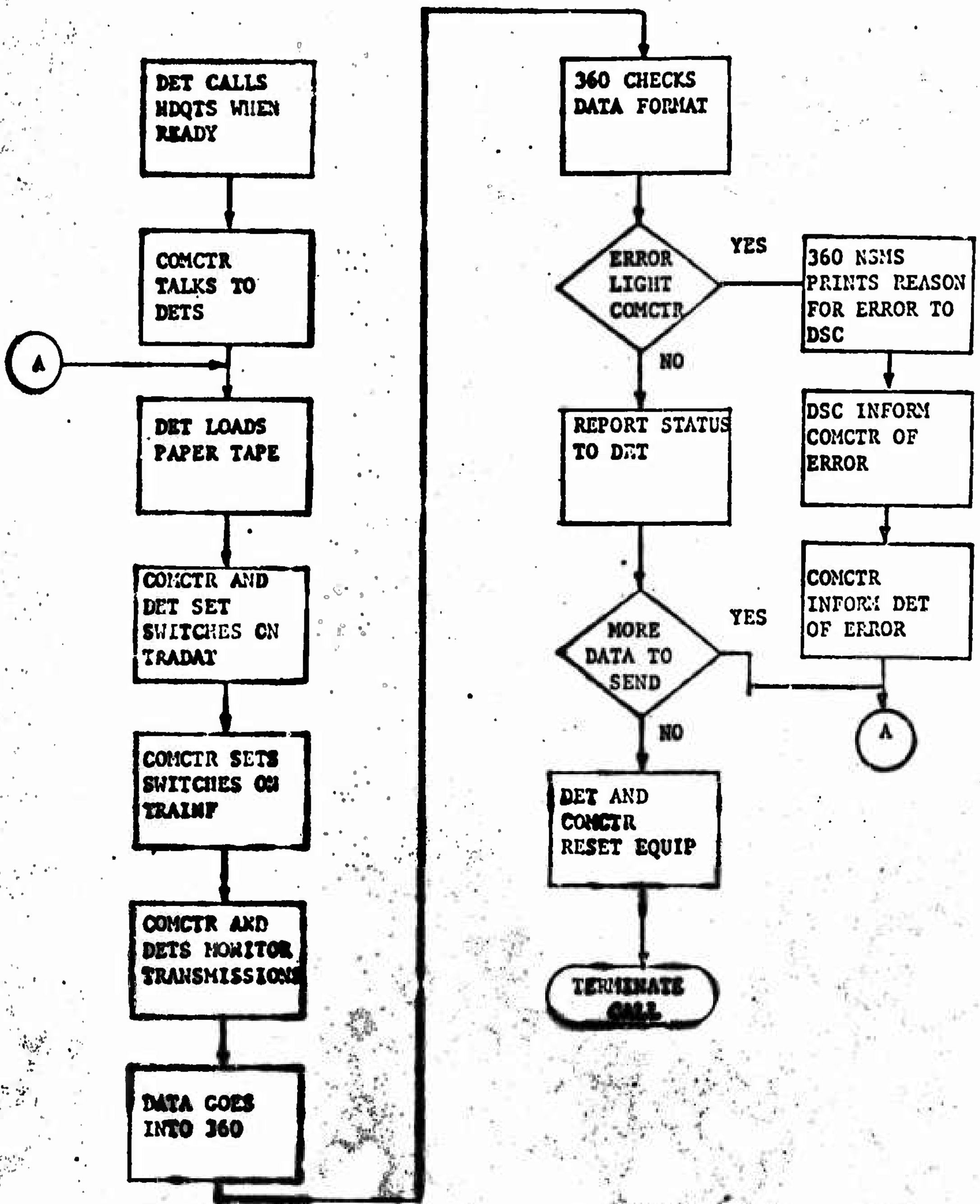


Figure 2-A (Continued)

CURRENT SYSTEM

2. TRANSMISSION AND RECEIPT OF UNCLASSIFIED MESSAGE DATA

A. HEADQUARTERS ORIGINATED   B. DET ORIGINATED

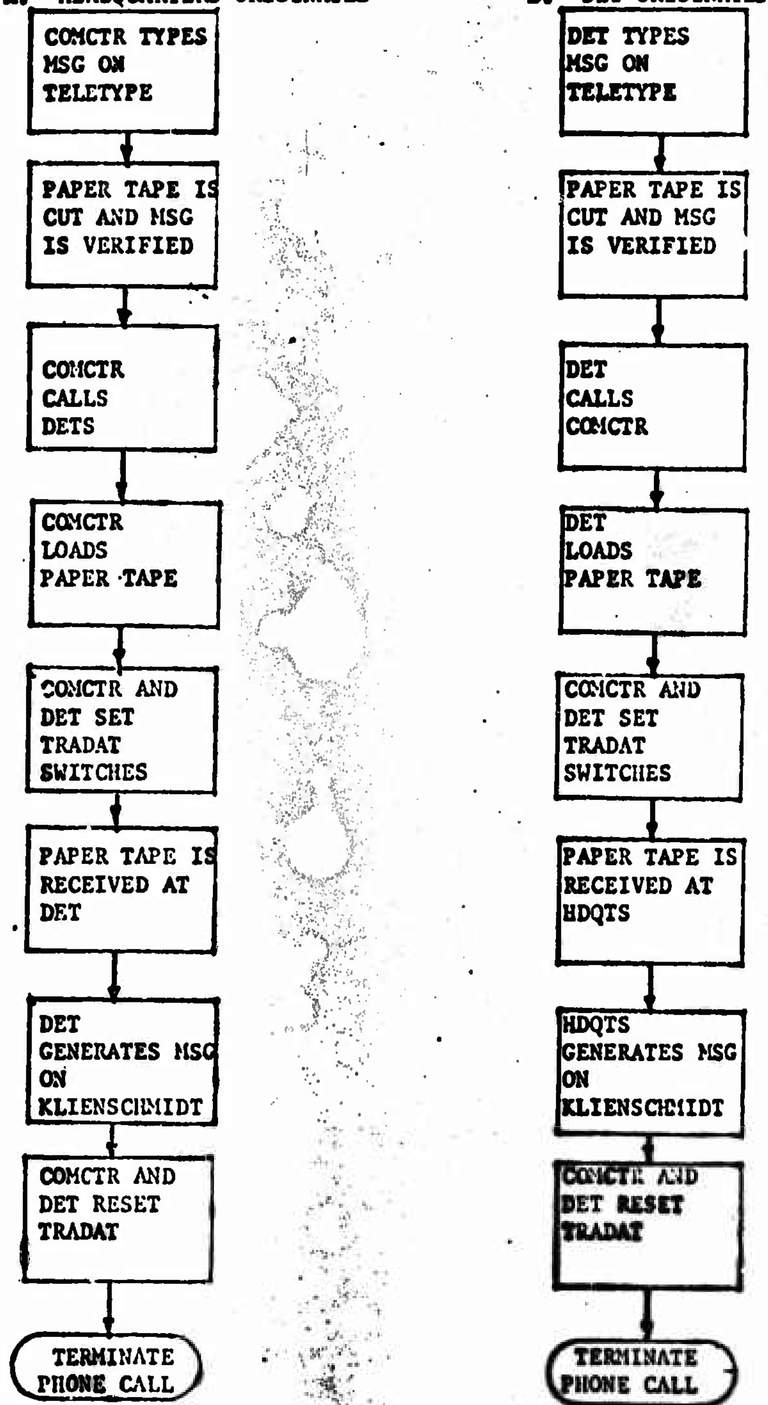
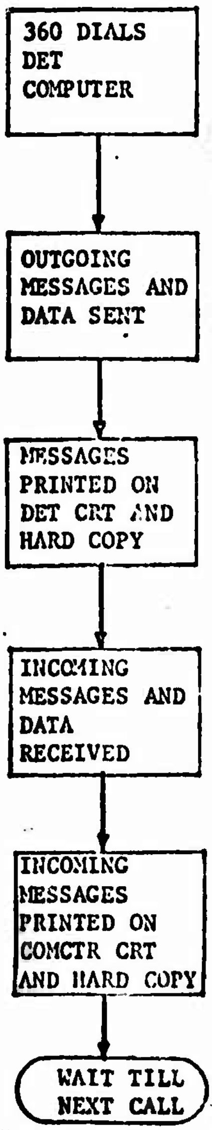


Figure 2-A (Continued)

UPDATED SYSTEM OF HANDLING
DOPPLER, MEMORY, FIXED FREQUENCY AND UNCLASSIFIED MESSAGE DATA

A. TRANSMISSION AND RECEIPT OF DATA



B. MESSAGE PREPARATION

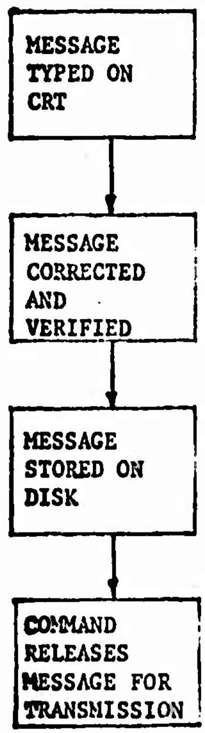


Table 1-A

SUMMARY OF EQUIPMENTS DELETED WITH INITIAL IMPLEMENTATION OF NEW SYSTEM

1. PAPER TAPE PUNCHES
2. PAPER TAPE READERS
3. TRADATS AND TRADAT INTERFACES
4. 7702'S
5. DIGITIZER
6. HEADER/TAILER
7. TIME RECOVERY AND MEMORY READOUT UNIT
8. SATELLITE MEMORY SIMULATOR
9. KLIENSCHMIDT TYPEWRITER
10. AN/UYK COMPUTER BR-130
11. MAGNETIC TAPE UNITS BR-170A
12. MAGNETIC TAPE CONTROLLER BR-192A
13. PAPER TAPE CONTROLLER BR-140
14. TYPEWRITER BR-185
15. DISPLAY FUNCTIONS OF DIGITAL CONTROL UNIT
16. HYPERION NIXIE DISPLAYS

Table 2-A

Comparative Communication Speeds

TYPE OF DATA	APPROX. TIME TO SEND AVERAGE LENGTH UNDER CURRENT SYSTEM INCLUDING MANUAL SWITCHES	EST. TIME TO SEND SAME DATA UNDER PROPOSED SYSTEM
DOPPLER PASS	80 seconds	20 seconds
MEMORY PASS	320 seconds	120 seconds
UNCLASSIFIED MESSAGE DATA	70 seconds	16 seconds
INJD TAPE	480 seconds	280 seconds

PHILCO Ford

Intra Company

16 October 1973

DNSDP-JTW-084

To: G. R. Hickcox

From: J. T. Witherspoon

Subject: Transit Operational Network Manning

Reference: Trip Report - Naval Astronautics Group, Pt. Mugu
DNSDP-JTW-080, dated 10/15/73

I called LCmdr. Klass Monday to clarify some of the numbers quoted in the referenced trip report. He provided the following additional information:

Detachment A (Maine)

Military	11	Operators	16
Civilian	15	Maintainers	6
	26	Administrative	3
		Officer in Charge	1
			26

Detachment B (Minnesota)

Military	31	Operators	25
Civilian	13	Maintainers	8
	44	Administrative	9
		Officer in Charge	1
		Asst. Officer in Charge	1
			44

Detachment C (Hawaii)

Military	7	Operators	10
Civilian	8	Maintainers	3
	15	Administrative	1
		Officer in Charge	1
			15

__Detachment D__ (Laguna Peak)

Military	17	Operators	23
Civilian	17	Maintainers	7
	34	Administrative	2
		Officer in Charge	1
		Asst. Officer in Charge	1
			34

__Headquarters__

- Computer Center - 22 personnel
- Control Center - 21 personnel
    - 7 Satellite Duty Controllers
    - 12 Comm Specialists
- Performance Analysis Group - 23 personnel
    - 6 Operational Analysts
    - 6 Performance Evaluators
    - 7 Computer Programmers
    - 2 Administrative
- Satellite Launch Division - 6 personnel

All locations operate on a four shift basis. Normal headquarters shift complement is:

- 3 Comput[illegible]ators
- 2 Comm S[illegible]sts
- 1 Satelli[illegible]ty Controller
- 1 Duty Officer

J. T. Witherspoon

J. T. Witherspoon

/sc

cc: Distribution A
R. Bryan
F. Chethik
D. Middlebrook
C. Rieker
R. Haislet

PHILCO Ford

Intra Company

15 October 1973

DNSDP-JTW-080

To: G. R. Hickcox

From: J. T. Witherspoon

Subject: Trip Report, Naval Astronautics Group, Point Mugu Naval Air Station

Messrs. R. Bryan, O. Holzborn, K. Jutzi, D. Middlebrook, D. Potter and the undersigned visited the subject facility on October 12 to become more familiar with the Navy Navigation Satellite System (NNSS), and with TRANET, the Transit Operational Network.

The Naval Astronautics Group (NAG) is responsible for operations of the Tranet. The group includes 245 people at 4 CONUS locations and operates on a $3.5 million annual budget. Principle military personnel are:

Capt. W. A. Lebert, CO
Cmdr. D. S. Caukins, Exec Off
Cmdr. A. J. Thayer, Ops Off
LCmdr. J. V. Klass, Duty Off
LCmdr. T. R. Brett, Duty Off
LCmdr. M. C. Murray, Duty Off
LCmdr. G. Watson, Duty Off

Principle facilities and functions are:

Point Mugu NAS - 154 personnel

Operations Center - 21
Computer Center - 22
Tracking/Injection Facility - 34
Performance Analysis Div - 23
Satellite Launch Div - 6
HQ Staff - 48

Maine - 25 personnel, 3/shift

Tracking/Injection Facility

Hawaii - 16 personnel, 2/shift

Tracking Facility

Minnesota - 50 personnel, 4/shift

Tracking/Injection Facility

Capt. Lebert met with us for an hour in the morning during which time he described the accomplishments of his group, frequently emphasizing the cost effectiveness and self-sufficiency of his operation. In addition to routine operation and maintenance of ground facilities, NAG personnel do all hardware engineering changes, maintain and upgrade computer programs, process and analyze satellite telemetry, schedule and manage new satellite launches, provide their own documentation and training, and manage their own logistic system.

Operations Center

LCmdr. Klass briefed us on the system operations and took us through the Operations Center. Much of the equipment in this center was originally provided by Philco-Ford WDL. It includes computer driven alphanumeric status wall boards, operating consoles, a computer data terminal, and various manual status charts. We were impressed by the simplicity and effectiveness of the operation which requires a single operations controller. While there, we witnessed the results of a half-dozen tracking passes including one in which the processor detected a timing error of 20 sec at one of the remote sites.

One of the more critical operations functions is satellite injection, the process of reloading the satellites with navigation data. This process occurs approximately twice daily for each of five satellites or ten times a day. Injections are schedules so that at least two injection stations can view the satellite during the process. The injection requires 24,917 bits and is accomplished in 15 seconds of transmission time. It is timed to occur between the satellite 2 minute broadcasts so as to minimize the impact to a current user. Each injection is followed by a 2 minute telemetry transmission from the satellite which is monitored by both injection sites. If both sites agree that injection was unsuccessful, the process is automatically repeated between the next navigation broadcast. After the primary injection station has made three unsuccessful tries, the secondary injection station takes over and makes three tries. Thus six tries can be made during each scheduled injection pass. This process has failed only four times in the last 15,000 or so injections. Injection scheduling is still done manually because of the many variables involved. This function is critical to a smooth, reliable operation and is one which we must emphasize more in the DNSDP planning. According to Capt. Lebert, the system operational availability over the last year has been 0.9997.

Computer Center

NAG operates a dedicated computational center which includes an IBM 7094, and two 360/40's. The 7094 is backed up by four other 7094's in the Base Data Processing Facility. The back-up must be used about five times a month. The 7094 is used for the orbit determination computations which are required approximately ten times a day. Each determination requires 2.7 billion computations and takes 93 minutes. Each orbit determination results in a 250k bit message which is transmitted to the appropriate injection stations via an IBM 7702 tape-to-tape system. These messages are prepared for 3 12 hour injection periods. Normally only the message for the first 12 hour "cluster" is used since subsequent tracking data will be used to update the message. However, if for some reason bad tracking data or a faulty computer prevents the determination of a new set of messages at the end of the first 12 hour "cluster," the second message from the previous cluster is available for injection into the satellite. This procedure allows for maintenance of satellite navigation data in the event of Computer Center failures in excess of 24 hours.

Injection/Tracking Facility

We were shown through the Injection/Tracking Facility by LCmdr. Watson. This facility includes a 60-ft X-Y Antenna (provided by Philco-Ford WDL), a quad-helix, dual BRN-3 tracking receiver/navigation computer, an 8 kW command transmitter, dual rubidium time standards, an AN/YUK-1 data processor, various data transmission and data handling equipment, simulation and test equipment. Command and telemetry frequencies are classified. The command system is a multi tone system; telemetry is an IRIG FM/FM system with 35 channels including subcommutation. All antenna pointing is done from computer driven tapes using the WDL antenna controller. The station supports approximately 20 passes a day of which 3 to 5 are injection passes. Tracking passes require 20 minutes of set up plus 20 minutes of actual tracking. Injection passes require approximately 1 hour including set-up, readiness tests, injection and tracking. Total site manning is 37, four shifts, 4 operators per shift, 2 maintainers per shift. There are plans to consolidate O&M functions to reduce the number of personnel required. We arrived during an injection pass which was annotated by LCmdr. Watson as follows:

The site receives a 250,000 bit injection message from the computing center approximately 60 minutes before the pass. This tape is duplicated upon receipt for safety, then loaded into the AN/YUK-1. The tape contains all data for the satellite injection, time oriented event sequences for the ground equipment, antenna pointing data for the antenna. Station readiness is tested by simulating the actual pass. Injection data is fed to the command transmitter, then into a "satellite simulator" which in turn sends navigation signals to the navigation receivers, which generate

tracking data which is sent to the navigation processor which computes a position fix. If the results are valid, the station is ready to support. All real-time functions during the pass are controlled by a sequencer called the Digital Control Unit (DCU) a device designed and built by the personnel at this site.

The BRN-3 Navigation Sets at this site are the type which are used by the submarines. This equipment required six racks which occupied an entire wall. All data processing and navigation equipment was contained in an RFI enclosure. The reason given for the enclosure was security. However there is evidently mutual interference between equipment within the room much of which is in the form of locally fabricated prototypes in non-RFI racks. Power reliability and stability is also a major source of trouble.

The AN/YUK-1 site computers are scheduled for replacement soon.

Satellite Clocks

The methods used by NAG to monitor and maintain system time are of particular interest in that the same procedures are applicable to DNSS. The time standard at the injection facility at Pt. Mugu is considered to be the master clock. After each tracking pass, the computing center estimates the timing error between that satellite/site and the master clock. This estimate is automatically provided to the operations controller within a few minutes of the pass. The estimated error is treated as a satellite clock error, i.e. the tracking station error is assumed to be zero. However, since most passes are covered by two sites, site peculiar errors can be estimated by an experienced controller and fed back to the tracking site by voice for manual correction. The accumulated error for each satellite is carried on the master status board. During our visit, errors for the 5 satellites were listed as -8, +2, -10, +4, -7 microseconds. The satellite clocks can be reset in increments of 10 μs during each injection. Criteria for when to reset is derived from the navigation error which is computed for each station for each pass. One of the tracking sites is co-located with a Naval observatory time standard (HAW) so that the synchronization errors between this site and the master clock at Pt. Mugu represents system time synchronization relative to other Navy operated navigation systems.

A bibliography of applicable documentation was obtained and is attached.

A pictorial supplement to the NNSS System Manual is available in the DNSDP Reference File.

Conclusions

NAG is a small, effective organization which includes many highly trained personnel. Any consideration of future DNSS configurations must address the question of how these people, their existing expertise, and their existing facilities could be used. Although the technology they are using is not applicable to DNSS, the procedures and techniques they have developed for system operations and control are extremely effective (as compared to, for example, the SCF).

This visit suggests several areas worthly of our further consideration:

- An operational analysis of the satellite injection process using existing NAG procedures and timelines as a basis.
- Design of man/machine interfaces for the operations center derived from existing NAG control center layouts, summary messages, alarm messages, performance checks.
- Use of the Pt. Mugu injection station for T&C functions for Phase I by adding a stand-alone SGLS system.
- Design monitor status around new NAG site processors, plan to get processors GFE, use NAG software development, particularly communication interfaces.

J. T. Witherspoon

J. T. Witherspoon

/sc

Attachment

cc: Distribution A
R. Bryan
F. Chethik
D. Middlebrook
C. Rieker

Appendix A

NAVASTROGRU PUBLICATIONS LIST

INJFAC 1-1, Part 1--System Description and Operation

INJFAC 1-1, Part 2--System Planned Maintenance

INJAC 1-2, Volumes 1, 2, and 3--Philco 60-Foot Antenna Operation and Maintenance

INJFAC 1-10--Satellite Simulator Operation and Maintenance

INJFAC 1-11A--Transmitter Operation and Maintenance

INJFAC 1-12--Modulation Monitor Operation and Maintenance

INJFAC 1-13--Transmitter Monitor Converter Operation and Maintenance

INJFAC 1-14A--Time and Frequency Control Operation and Maintenance

INJFAC 1-15--Spectrum Display Unit and Signal Monitor Operation and Maintenance

INJFAC 1-16--Telemetry and Satellite Command Equipment Operation and Maintenance

INJFAC 1-16, Supplement 1--Telemetry Compositor Mod 2 Operation and Maintenance

INJFAC 1-17--AN/BRN-3 Alternate Reader and Punch Equipment Operation and Maintenance

INJFAC 1-18--Digital Control Unit Operation and Maintenance

INJFAC 1-20--Interior Communications Systems Operation and Maintenance

INJFAC 1-21--Antenna Data Input System Laguna Peak Operation and Maintenance

NAG Technote 34-65--Telemetry Reception Procedures, 16 June 1965

APL Publication: (Unclassified) TG-623--Processor Test Unit by M. Newcomer, Nov. 1964

Machine Reference Manual M250-2019--TRW-130 AN/UYK-1

Technical Manual M250-2U1 for AN/UYK-1 (TRW-130)--Digital Computer Volume 1 of 2

Technical Manual M120-2U3--TRW-140 Controller

Technical Manual M250-2U47--TRW-192/170 Magnetic Tape Set

Utility Technical Manual--Operation and Maintenance 60-Foot, X-Y Mounted High-Gain Antenna System Philco WDL-TM-6001-3 (15 March 1963)

Operation and Maintenance Data--Rucker Model S-1345 Hydraulic Power Plant

Operation and Maintenance Data--Rucker Model S-1346 Hydraulic Manifold Assembly

Maintenance Manual--Perforated Tape Reader Models 3500 and B-3000

Operation and Maintenance Manual--Kleinschmidt Printer

Operating Instructions--Standby Power Supply Model 311A

Operating Instructions--Rubidium Frequency Standard Model 304-B

Instruction Manual--Crystal Controlled Dual Frequency PM Signal Generator SRA 612

Instruction Manual--Time Code Generator Model 7140, AstroData

Operating and Service Manual--Electric Counter 5245L, Hewlett-Packard

INJFAC 1-25--Universal Standby Power Supply, Operation and Maintenance

Operation and Maintenance Manual--Perforated Tape Handler Models 4566A, B-4566A, 4566ALCR, B-4566ALCR

Instruction Manual--Models LA-5-03B, LA-50-03 BM, Regulated Power Supplies, Lambda Electronics

Operating and Service Manual--115CR Frequency Divider and Digital Clock

Tape Reader Manual--CDC-350

Power Supply Manual--Dressen-Barnes 21-102A

Power Supply Manual--Dressen-Barnes 22-217

Instruction Manual--Data Recorder Model 906, Honeywell

Instruction Manual--Data Recorder Amplifier Type T6GA-500, Honeywell

Instruction Manual--Time Code Generator Type 6190, AstroData

Instruction Manual--Commutator Hold Synchronizer, APL

Operating and Service Manual--200TR Precision Telemeter Test Oscillator, Hewlett-Packard

Technical Manual--GD-500 Transistorized Phase Lock Discriminator, Vector Manufacturing Co.

Technical Manual--GTCU-500 Tape Compensation Unit, Vector Manufacturing Co.

Operating and Service Manual--450CR Automatic DC Digital Voltmeter, Hewlett-Packard

Operating and Service Manual--5532A Electronic Counter, Hewlett-Packard

Operation and Maintenance Manual--T6GA-500 Galvanometer Amplifier, Heiland Div. Honeywell Co.

Operation and Maintenance Manual--906c Visicorder, Heiland Div. Honeywell Co.

Instruction Manual--FR1200 Magnetic Tape Recorder, Ampex Corp.

Instruction Manual--6190-600 Time Code Generator, AstroData Inc.

Technical Manual--SE-10 Automatic Bulk Head Tape Degausser, Ampex Corp.

Instruction Manual--Model 905 WWV Receiver, Beckman

Operating and Service Manual--Model 599-CS VLF Receiver, Textran

Instruction Manual--EECO 880 VLF Receiver, Electronic Eng.

Operating and Service Manual--Model 130C Oscilloscope, Hewlett-Packard

Operating and Maintenance Manual--Model 115CR Frequency Divider and Digital Clock, Hewlett-Packard

Operating and Maintenance Manual--Model 680 Strip-Chart Recorder, Moseley

Operating Instructions--Model A Recorder, Rustrak

Instruction Manual--VLF Standby Power Supply, 1 mc Distribution Amp

Instruction Manual--Model 2.5 Frequency Standard, Sulzer Labs.

Instructions--Model 5P Power Supply (Addendum to Model 2.5 Pre-Standard Instruction Manual), Sulzer Labs.

Standard Instruction Manual Addendum to Model 2.5 Frequency--Model SA6-1 Buffer Amplifier, Sulzer Labs.

Operating and Service Manual--Model 725AR Standby Power Supply, Hewlett-Packard

Instructions--Model 1 Linear Phase Detector, Sulzer Labs

OPTRAC 1-11--OPTRAC Components, Operation and Maintenance

OPTRAC 3-10--Time Recovery and Memory Readout Unit and Satellite Memory Simulator Operation and Maintenance

OPTRAC 3-11--Stereo Amplifier Operation and Maintenance

OPTRAC 3-11--Helix Antenna Operation and Maintenance

Equipment Manual--Radio Receiver R-1132-BRN-3 NAVSHIPS 94365, Vol II

NAG-SPALT-NAG-BRN-0001--Modifications to Radio Receiver R-1132 AN/BRN-3, for use in Navy Astronautics Group Tracking and Injection Stations, W/C2, Dec. 3, 1965

DC Coupling Preamplifier Sanborn Models 850-1300; 850-1300B

DC Coupling Preamplifier Sanborn Models 850-1300D; 850-1300Z

Instruction Manual Model 2.5 Frequency Standard--5 MC Off-Set Standard Model 2.5 (Mod for 5 mc output), Sulzer

Operating and Service Manual--725AR Standby Power Supply, Hewlett-Packard

Instructions--Model HTP-115CR Digital Clock, Hewlett-Packard

Recording System, Sanborn Models 856-5460N, 856-5460", 858-5460--Model 356-300W Six Channel Recorder, Sanborn

Operating and Service Manual--1781B Delay Generator (P/U for Mod. 175A Scope) Hewlett-Packard

Augmented Tracking Antenna, Pedestal, and Control System Manual--Model J225 Tracking Antenna Pedestal, Scientific Atlanta

Technical Manual--Radio Navigation Set AN/BRN-3 Vol I through Vol III, Westinghouse

TS-65-161--Satellite Memory Simulator, NOTS China Lake

INJFAC 1-1 Appendix C--Voltage Monitor Panel Mod, NOTS China Lake

Header-Tailer Programmer HTP-01, Decisional

INJFAC 1-1 Appendix C--Oscilloscope Signal Switching Unit, NOTS China Lake

Operating and Service Manual--175A Oscilloscope, Hewlett-Packard

Instruction Manual--[illegible]M-8A Doppler Digitizer and Station Clock, Abacus, Inc.

Instruction Manual--Model 420 Tape Perforator, Tally Corp.

Operation Instructions--Model 310-C Standby Power Supply, General Technology Corporation

Instruction Manual--Models LE101, LE101M, LE101FM Regulated Power Supplies, Lambda Electronics

Instruction Manual--Model HI-300-6 Display Assembly, Hyperion

Instruction Manual--EECO 330 VLF Receiver, Electronics Engineering Co. of California

COMNET 1-11, Data Buffer Synchronizer Operation and Maintenance

COMNET 2-12, Data Transmission Terminal Operation and Maintenance

COMNET 2-12, Supplement A--Data Printer Control Operation and Maintenance

COMNET 2-12, Supplement B--TRADAT Interface Operation and Maintenance

COMNET 2-12, Supplement C--Communications and Switching Distribution Unit Operation and Maintenance

COMNET 2-13, Model 420 Perforator with NAVASTROGRU Modifications Operation and Maintenance

Installation and Operating Manual--CHB35A PA Amplifier, Bogen

Installation and Operating Manual--MU15A PA Amplifier, Bogen

Installation and Operating Manual--MU10A PA Amplifier, Bogen

Installation and Operating Manual--T-C-4906 Chief Master Station, Talk-A-Phone Co.

Installation and Operating Manual--T-C-42 Chief Staff Station, Talk-A-Phone Co.

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 6592D AIR BASE GROUP (AFSC)
LOS ANGELES AIR FORCE STATION, PO BOX 92960, WORLDWAY POSTAL CENTER
LOS ANGELES, CALIFORNIA 90009

REPLY TO ATTN OF: YE

28 December 1973

SUBJECT: Global Positioning System (GPS) Control Segment Alternatives

TO: Philco-Ford Corp.
ATTN: Mr Gene Hickcox

1. The GPS JPO and visitors from various DOD agencies were briefed by your GPS GS/UE definition team during the 18-19 December 1973 TD Meeting. One topic was the relative merits of adapting several existing DOD facilities to provide the Phase I GPS Control Segment. Four DOD organizations were considered: (1) AFSCF, (2) 4000 Aerospace Applications Group, (3) NAG, and (4) NRL/NWL. The purpose of this letter is to outline a Control Segment configuration which uses the resources of three, and possibly four, of the above named organizations.

2. The configuration, as described in Attachment 1, incorporates a combined upload and monitor station, Site 3, which uses a novel method to insure proper loading of the space vehicle navigation subsystem. Site 3 should provide the capability to calibrate space vehicle clocks immediately prior to the test period over Southwestern ConUS, and might be able to operate with satellites appearing North of the station, 12 or so hours after data upload.

3. The remaining attachments are reports of trips and telephone conversations which relate to Attachment 1. Your team should be prepared to discuss the various capability and cost trade-offs which contrast the configuration described in Attachment 1 with others you are considering during the 10 January 1974 meeting at SAMSO.

RECD WDLCC Dec 31 2 31 PM '73

Richard H. Jessen

RICHARD H. JESSEN, Lt Col, USAF
Director, Engineering

WDLCC

SERIAL 33555
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1. Control Segment Deployment Using the NAG
2. Trip Report to NAG, 13 Dec 73
3. Telecon 7 Dec 73
4. Visit to NAG, 19 Nov 73
5. Trip Report to NRL & Blossom Pt. Maryland, 20-21 Nov 73

GLOBAL POSITIONING SYSTEM - PHASE I

Control Segment Deployment Using the Navy Astronautics Group

1. INTRODUCTION

Phase I of the Global Positioning System (GPS) Control Segment will use, where practical, existing DOD resources in the form of facilities, hardware, and personnel. A discussion of how the Navy Astronautics Group of Pt Mugu, California might be used as an operating agency for the GPS Control Segment follows:

2. BACKGROUND

Since 1967, the Navy Astronautics Group (NAG) has served as the operating agency for the Navy Navigation Satellite System (NNSS). Using the TRANSIT satellites, the NNSS provides accurate navigation fixes to several classes of users at approximately two-hour intervals. NAG observes the motion of the TRANSIT satellites using four ground stations. A facility at Pt Mugu serves to combine measurement data, compute orbits, predict ephemerides for the satellites, and format each ephemeris for uploading into satellite memory. The Spring 1971 issue of "Navigation: Journal of the Institute of Navigation" contains a discussion of the NNSS.

3. CANDIDATE CONFIGURATION

a. Pt Mugu

The GPS Master Control Station (MCS) and one Monitor Station (MS) will be co-located with the NAG facilities at Pt Mugu. The NAG staff will be augmented to support GPS operations. The MCS will access NAG and GPS--peculiar telecommunications to three other sites which complete the Phase I GPS Control Segment. The MCS will perform the combining of measurement and historical data, orbit determination, ephemerides generation, and space vehicle navigation subsystem upload message formatting on a new, dedicated computing system. The MCS can access the NAG WATS for 1200 baud data communications to NWL for external computational support or for communications with other agencies required for GPS operations.

b. Wahiawa, Hawaii

The NAG Hawaii facility will house a GPS Monitor Station and provide a telecommunications link to the MCS at Pt Mugu.

c. Site 3

Site 3 is located at an operating DOD facility in the Northwest CONUS or Alaska and includes an Upload Station and Monitor Station. Site

selection is based on (1) space vehicle visibility for data message upload, (2) access to existing telecommunications which could be connected to the MCS, and (3) space vehicle monitoring geometry.

The Upload Station addresses the space vehicle by means of an entry preamble which is loaded as cipher text by the AFSCF during telemetry readout. The proper preamble allows the Upload Station to access the space vehicle navigation subsystem and load it with navigation data in the clear. Additional words which serve to verify proper loading are included in the upload message. Verifications of proper loading of each message block is indicated by the state of certain bits in the L-band navigation data frame and S-band telemetry.

d. Site 4

Site 4 is located at an operating DOD facility which provides good space vehicle monitoring geometry and access to telecommunications to the MCS.

e. The AFSCF

The AFSCF is responsible for (1) placing the GPS space vehicles into the proper orbits immediately after launch, (2) space vehicle commanding and configuration control, (3) space vehicle telemetry readout, and (4) loading, as cipher text, the preamble word needed by the GPS Upload Station to access the navigation subsystem.

MEMORANDUM FOR THE RECORD

SUBJECT: Trip Report to NAG on 13 December 1973

1. Attendees:

Mr. Tom Smith	Satellite Program Manager	(AU)873-8702
Mr. Gary Kennedy	Computer System Analyst	
Mr. Charles Clark	Communication and Facilities	(AU)873-8067
Mr. Loren Campbell		(AU)873-8702
Mr. Pete Martin	TRANET	(AU)873-8007
Dr. Joseph Podorsek	Satellite Engineer	
Mr. Howard Newman	General Dynamics	
Mr. Jim Coxey	General Dynamics	
Mr. Robert DiPalma	Mellonics	

2. Purpose:

To examine the ground station system at the Naval Astronautics Group and acquaint General Dynamics and Mellonics with NAG's capabilities.

3. Discussions:

The location of several Navy remote installations were discussed. Some sites are operated by contract by New Mexico University while others are manned by foreign nationals.

The Navy uses a time shared commercial data line from Samoa to Hawaii. The NAG remote sites include Prospect Harbor, Maine: Rosemont, Minnesota; Laguna Peak, California; and Hawaii. To each station in Hawaii, Maine, and Minnesota, the Navy has dedicated C-2 conditioned lines consisting of 1 voice line (2 wires) and 2 data lines (4 wires). All lines have a 1200 baud capacity but are to be upgraded to 2000 bauds. Their modems are 202B Western Electric and are slated for eventual replacement by 208B or 209B models. The total cost for all 3 lines is $83,000 per year with annual depreciation reducing the cost each year. An example case was given in which another Navy command was allowed to use the lines for one hour each day at a rate of $12/hour.

Mr. Charles Clark stated the Navy Fleet Weather Service operated a 4800 baud unclassified data line between Hawaii and Guam at a cost of $9,300/month. This could possibly be used part time by GPS providing certain questions were answered (see next section). The daily time slots that are currently available are from 2300 to 0130 ZULU and 1100 to 1330 ZULU. It is also possible that slots of 10 to 20 minutes could become available.

A presentation by Mr. Gary Kennedy on the present and planned upgrading of the computational system followed. A copy of the viewgraph

presentation is attached. The present plan is to upgrade the network in the 1975 - 1977 time period (Hawaii excepted). In April of 1974, they will acquire a T&E remote station for debugging and initial tests. A PDP-11 computer is the leading contender. Machine language will be used for the remote sites, whereas PL-1 will be adopted for the H.Q. computer acquired in the 1978 - 1980 time period.

For the present Transit system, the downlink frequences are 150 and 400 MHz and the uplink is at 143 MHz. Downlink telemetry is at 50.8 bits/sec; 24 sec/frame; 5 frames; .6 sec for each channel. The injection message comprising the ephemeris data, memory data and commands consists of 640 words of 39 bits each (approximately 25,000 bits). Commanding bit rates over the auxiliary mode consists of 2 bits/sec (two tones) whereas the operational mode uses 1600 bit/sec rates.

4. Questions and Actions:

a. Mr. Clark requested a written response to these four questions concerning the possible GPS use of the Guam to Hawaii data link:

(1) How does GPS plan to input data into present system? (What equipment will be used?)

(2) Time required for each data transmission?

(3) Total time required daily for each data transmission?

(4) Can the data be segmented for transmission when time becomes available each day?

b. present Navy Transit satellites had battery lines of 5-6 years

Max Prola

MAX PROLA, Capt, USAF
Ground Station Division Engineer

1 Atch
Viewgraph Presentation

Memo for Record 11 December 1973

Subj: Telecon 7 Dec 73 - Tom Self/NAG and Capt Rennard

Mr Self was contacted to learn that neither of the 60-foot reflectors has ever been focused. He stated that the stiction problem in the Philco antenna occurred during checkout of the antenna by NAG in the early 1960s, and that the stiction had caused a few mounting bolts to be loosened. This contrasted a semantic misunderstanding which had lead me to believe that the reflector had separated from its pedestal. Philco was called in and welded the reflector down. Mr Self did not know whether or not this would cause problems in focusing.

Robert W. Rennard
ROBERT W RENNARD, Capt, USAF

Capt Rennard/31202/vp/27 Nov 1973

MEMORANDUM FOR THE RECORD

SUBJECT: Visit to Navy Astronautics Group - 19 Nov 1973

1. Persons Representing SAMSO:

Lt Col Dennis Capper	AFSCP/XP
Capt Robert Rennard	SAMSO/YEE
Tom Connor	Aerospace
Dr. Marshall Fitzgerald	Stanford Telecommunications, Inc.

2. NAG Personnel and Functional Area:

Cmdr Albert Thayer	Executive Officer
Lt Cmdr Watson	Laguna Peak Station
Charles Clark	telecommunications
Joseph Pokorsek	space vehicle
Tom Smith	system engineering
Gary Kennedy	computers
Thomas Self	antennas
Loren Campbell	software

3. Technical Discussions

a. DNSDP/DNSS Overview

Since some of the NAG personnel were not up to speed on the current JSPO plans, Cmdr Thayer requested Capt Rennard to give a short briefing on the functioning and plans for implementing DNSDP and the transition to DNSS. Questions on the satellite constellation and signal structure were answered. Emphasis on the ground segment and how it might interface with NAG operations was used to preface the day's discussions. Cmdr Thayer said that Capt Lebert would like to receive a copy of any document reflecting our current program plans. The JSPO will, therefore, forward a copy of the recent baseline document to him.

b. Telecommunications

Charles Clark presented data on the nature of the ground communications links and the types of data terminals being used. As stated in an earlier memo for the record; schedule 4, C2 conditioned, 4-wire lines are used to all remote sites. The Bell modems are type 202D rated at 2K baud. These modems will be replaced with 202E modems when they become available. The Port Hueneme to Makalapa, Hawaii circuit which shares the NAG leased line uses 4800 baud Bell 203A modems. NAG also has 202E data sets rated at 1200 baud for use on their WATS circuit. Clark stated that the Minnesota line currently has 20% utilization, and the Maine line has 33% utilization. The difference is due to the fact that the Maine circuit has a drop into Minnesota which accounts for some usage. AUTOVON has not been able to support 1200 baud data transmissions.

On a daily basis, NAG performs 66 doppler passes each requiring 72 seconds data transmission time and 20 data injection passes each requiring [illegible] seconds data transmission time. With modernization, these times will decrease from 72 to 30 seconds, and from [illegible] seconds to 315 seconds, approximately. Hawaii performs no injections, and the use of the Maine station for injections is undesirable since it has no parabolic antenna. Normally, a primary and backup station are used for injections. This results in a line usage total of [illegible] hours 1[illegible] minutes per month for doppler passes, and 1[illegible] hours 1[illegible] minutes per month for data injection passes, based on 2 stations operating on each pass. (This is my calculation and may be conservative.) Line usage to Hawaii by Port Hueneme is 12[illegible] hours per month. (Assuming 29 hours 5 minutes per station for doppler tracking and [illegible] hours [illegible] minutes per station for injections, this implies a 22% usage of the Hawaii line, and 14% usage of Japan and Minnesota lines, with 3% usage of the Maine line. Apparently NAG's usage statistics reflect a great deal of time on the companion 2-wire voice circuits.) There are other data transfers, but they do not seem to make an appreciable contribution to the line loadings.

c. Information Flow

Prior to each doppler tracking pass, Point Mugu sends out a message which is punched onto paper tape for pointing the 60Ft parabolic antenna, or identifies a catalogued tape for pointing the helical antennas. The station crew prepares a header for the doppler tracking tape, and readies other equipment for the tracking pass. The tape receives data relating to the differential in time between the satellite and station clocks, [illegible] second time interval marks, and data indicating the time to obtain a variable but preset doppler count. The doppler count on the tapes has been corrected for atmospheric path effects by the receiver, and is referred to as "vacuum doppler".

The Point Mugu built TRADAT transfers the tape data to a 360/40 at Point Mugu. The 360/40 checks the header information and performs reasonableness checks on the timing data. The 360/40 then generates a 36 hour concatenated doppler tracking data set which it places on a 2314 disc storage device. When a run is to be made on the 7094, the data needed is transferred to magnetic tape.

In a period of 1 hour 20 minutes, the 7094 generates 3 (of 4 possible) data injection tapes, one for each injection site. (APL is a back-up). These tapes differ due to changes in the data load caused by their geographical location, and by the limited communications data which is inserted on each tape. The tapes are sent to the remote sites via 7[illegible] tape controller transfers. A large amount of error correction data is included on the tapes for use at the satellites.

These tapes are also used to input data to a hardware injection simulator for verifying the format of the data and finding any erroneous data bits. This effort is performed by the 360/40. The remote stations verify that the satellite responded data load agrees with that sent, and reloads if necessary. Only 5 of 17000 passes have been unsuccessfully loaded.

Two minutes 36 seconds after completion of load verification, 2 minutes of current data on the vehicle is telemetered to the site. The data is forwarded to a second 360/40 for reduction. The remote

(sites) can also process the analog telemetry data manually using a strip recorder.

NAG rarely issues a command to the satellite. The commands, when needed, are voice requested by Point Mugu, and issued from the remote sites.

d. Computer Programs and Hardware

The orbit determination and ephemeris program, which runs on the IBM 7094 II, was written in the 7094 assembler language by APL. The software is serviceable - a pole - wander model was incorporated by NAG personnel some time ago. APL is writting a PL/I program which is supposed to incorporate the pre-processing done by one of the 360/40 computers, and is to provide a more modern approach to the mathematics involved in the orbit determination. The PL/I program is about 80% complete and APL is receiving 3 man-years of funding to continue their efforts. This new program will process data from only one satellite at a time.

NAG hopes to replace the 7094 by 1977 after an off-line demonstration of the software. The computer they choose will probably be a duplicate of the computer that the Pacific Missile Range (PMR) purchases to replace the 7094 computers they now have. NAG must retain compatibility in order to insure that they have an off-line back-up.

The NWL CELEST program was discussed. NAG is looking at several of its modules, but not for use as a total replacement for what they now have. When asked why they did not sponsor a TRANSIT version of CELEST, they had no real answer, but stated they did plan to look into it in greater depth.

Presently, the limited communications data is entered into the 7094 program about midway in the processing period. During this period, the machine room is physically secured and all external connections are severed. NAG has several thoughts about how they would add this data into the injection data tapes when using a multi-programmed computer. Presently, they do a hardware memory scrub, a check, and a re-scrub before letting external users back on to the 7094. They are toying around with adding the limited communications data with a specialized piece of equipment after a majority of the processing was done in a batch mode.

NAG has selected a mini-computer configuration for upgrading their remote sites to eliminate a great deal of manual data handling and control. They are awaiting for approval from higher headquarters before announcing the award. They feel it will take approximately 30 days to retrofit and adapt each station to the new capability. There is some in-house activity underway to define the software, but as in the past, the process will probably be evolutionary. The mini-computers are expandable from 2.5 Mbytes to 7.5 Mbytes and will have an operating system capable of rolling software segments in and out of core. Mr. Kennedy stated that I/O slots would be available, implying that a MKDP receiver could interface to the NAG mini-computer.

c. Antenna and RF Environment

NAG uses several versions of NAG-made spiral helix antennas, and two 60ft parabolic antennas. The Laguna Peak antenna was built by Philco and has a solid surface dish, while the Electronic Specialties antenna at Rosemount, Minnesota has a ½" screen dish. Both antennas are X-Y gimballed. At VHF and UHF, the antennas have a fairly large main lobe, so boresighting has not been performed. However, NAG has used a pointing offset to discriminate between close proximity satellites. Both antennas are specified to 1 milliradian pointing, but have not been verified. Neither antenna was ever boresighted and the Philco dish was shaken off by shuddering caused by stiction in the gimbal. Both antennas have low masking angles. Finding a place to establish a boresight reference which is above the horizon might be difficult at Laguna Peak since the occlusion caused by gimbal lock is in the most favorable direction.

3.125" hard coaxial cable is used to feed the antennas. It is routed through the pedestal and joints of the antenna. It may be possible to route S-band feeds in parallel, but further investigation is needed. It may be possible to establish a Cassegrain feed in the Philco antenna by mounting the S-band transmitter in the center of the dish. The Rosemount antenna will probably not accept this type of feed.

Grounding at Laguna Peak is established by three cross-tied radial grids which are interconnected by the RF feed. Periodic sprinkling with brine is needed to assure adequate conductivity. The antenna grounding is a 500,000 circular mil bus.

Laguna Peak has a 500KVA service with a UIPS rated at 200KVA. Current usage at Laguna Peak is approximately 110KVA.

4. Action Items

a. SAMSO/YE is to provide a copy of the planning document to Navy Astronautics Group.

b. Mr. Charles Clark/NAG will provide further data on connecting Hawaii to Agana Terminal, Guam and the name of a point of contact at DCAPAC.

SIGNED

ROBERT W REINHARD, Capt., USAF
Chief, Ground Stations Division

2 Atch
1. NAG Ltr, 28 Aug 73
2. Document, Navy Nav Sat Sys, Jan 67

Capt Prola/31202/vp/29 Nov 73

30 NOV 1973

MEMORANDUM FOR THE RECORD

SUBJECT: Trip Report to Naval Research Laboratory (NRL) and Blossom Pt. Maryland 20-21 Nov 1973

1. Attendees:

Col Jessen
Col Penninger
Maj Yarborough
Capt Birnbaum
Capt Wilson
Capt Collins
Capt Prola
NRL Personnel
Def. Mapping Agency Personnel
Navy and Army Personnel

2. Purpose:

To participate in the NRL TIMATION Symposium and visit the Blossom Point ground station.

3. Discussions:

NRL personnel presented various briefings regarding the TIMATION system. TIMATION I and II were touched briefly but the majority of the presentations concerned TIMATION III (NTS-1).

Navigation accuracies from the TIMATION II system were briefly discussed. Using range/doppler measurements and the 150 and 400 MHz signals for ionospheric corrections, the results for 43 passes were presented as a 64 meter RMS circular error prediction. Differences between daytime and nighttime ionospheric measurements at 400 MHz were cited to be on the order of 700 meters. In addition, time standard transfer measurements between the U.S. Naval Observatory and an Australian station citing a .110 microsecond RMS error. A comparison of the TIMATION II system time with the Greenwich Standard time yielded a 233 nanosecond RMS difference.

The main reasons for the hoped-for improvements with the TIMATION III (NTS-1) system are the removal of drag effects, use of higher frequencies for better ionospheric corrections, and higher elevation passes (greater than 50°) resulting from the new orbits. Measurements of the atmospheric effects are to be made from the Chesapeake Bay Station and another site at frequencies of 335 and 1580 MHz.

The NRL point of contact for the TIMATION III ground station system is Mr. Jim Buisson. The envisioned ground station system consists of three range and doppler stations:

Chesapeake Bay, (ETR)Florida, and NRL (an experimental station), and three doppler only stations:

Seychelles (Indian Ocean), American Samoa, and Guam. Eventually all six stations will have range and doppler capability. The control center will be located at NRL with Autodin links to the tracking stations and to APL and NWL. When the tracking station satellite visibility areas are considered, several narrow banded blind areas appear in the southern hemisphere. Geodesy Laser Tracking Stations will be located at Greenbelt, Md; Wallops Island, Va; ETR, Fl; Bermuda; Grand Turk; Arrequipa, Peru; Johannesburg, Africa; Natal, Brazil; and San Diego, Ca.

Several data collection schemes are being considered. One of the more favorable formats involves 10 range rate observations over 400 seconds and range measurements every 3 minutes.

A briefing on the operation and design of the TIMATION III laser tracking system followed. The main points emphasized in the laser briefing concerned the proper selection of the reflector cube corner radius and the calculations for estimating the final numbers of photoelectrons received.

In discussing their orbit determination program NRL cited a potential model with 480 gravitational terms, 10 satellites, and 70-80 ground stations. Influences from the tides (Love's number) and radiation pressure were also examined according to level of truncation effects. In general, the estimated errors due to any single effect were less than 2 meters. The errors due to tropospheric modeling were assumed to be 10%.

For any orbit prediction cycle, 4 days of orbit data are used to generate synthetic data for 2 days and a best fit with error sources is made for the next 2 days. The new orbit prediction is thus generated for the next 4 days and compared with actual observations. A table giving the predicted satellite position for 48 hours for various orbits follows:

Orbit	Maximum Orbit Error(m)
8 hr, 125°	1.5 meters
8 hr, 60°	2.5
12 hr, 125°	3.3
12 hr, 60°	4.6

The figures were for along track errors and would correspond to approximately 1/3 the error on the ground. Concerning the solar radiation pressure modeling problem, it was felt the 12 hour orbit would be easier to model than the 8 hour orbit. Bob Hill is converting the Celesto orbital determination program to the Univac 1108 computer.

On 21 Nov 73, a tour of the Blossom Point tracking station was given. The station is undergoing extensive modifications. The latest antenna installed is a Datron Inc. 30ft diameter parabolic dish with a 10 degree

beam width, 1.2 degree minimum elevation angle, and 720 degree total azimuth restriction due to the cable feed. Total cost for the antenna and its installation was $250 K. Transmitter power up to 1.5 KW is supplied by pressurized coaxial lines. Antenna pointing is accomplished by manual control, paper tape drive or eventually by computer control. Present foreseen scheduling will include 12 passes/day of Solrad (16 minutes each) and 6 passes/day of TIMATION. The projected use for the TIMATION program will be 5 hours/day. A backup station is located at Vandenburg AFB. Future plans are for the construction of another 50ft dish at Blossom Pt. for the Solrad program. Sharp rejection filters are used because of the complex RFI environment in the area. RFI surveys of Blossom Pt. have been performed. Most of the station equipment is dated an very little of the data is digitized at Blossom Pt. before sending it to NRL.

Mr. Robert A. Gouker (Autovon 287-2719) of the Defense Mapping Agency(DMA) stated he would be interested in organizing a meeting with JPO personnel at some convenient future date in Washington to discuss DMA's capabilities and interests in relation to our program.

SIGNED

MAX PROLA, Capt., USAF
Ground Stations Division Engineer

6.2 SAC

The following data refers to existing SAC facilities.

PHILCO Ford

Intra Company

20 November 1973
DNSDP-P-017-OCH

TO: D. R. Potter

FROM: O. C. Holzborn

SUBJECT: Visit to Detachment 1, SAC 4000th AAG

On 14 and 15 November, a visit to Detachment 1 of the SAC 4000th AAG was held. The attendees are listed below:

Captain R. C. Collins	(SAMSO)
Captain M. Prola	(SAMSO)
James T. Carroll	(Philco-Ford)
Owen C. Holzborn	(Philco-Ford)
J. E. Coxey	(GDE)
H. L. Newman	(GDE)
R. A. Di Palma	(Litton-Mellonics)
P. M. Fitzgerald	(STI)

Detachment 1 is located at Fairchild AFB near Spokane, Washington. It serves as one of two Command Relay Stations (CRS) supporting the 4000th AAG Command and Control Center at Offutt AFB. The key Detachment 1 personnel who conducted briefing and demonstrations are listed below:

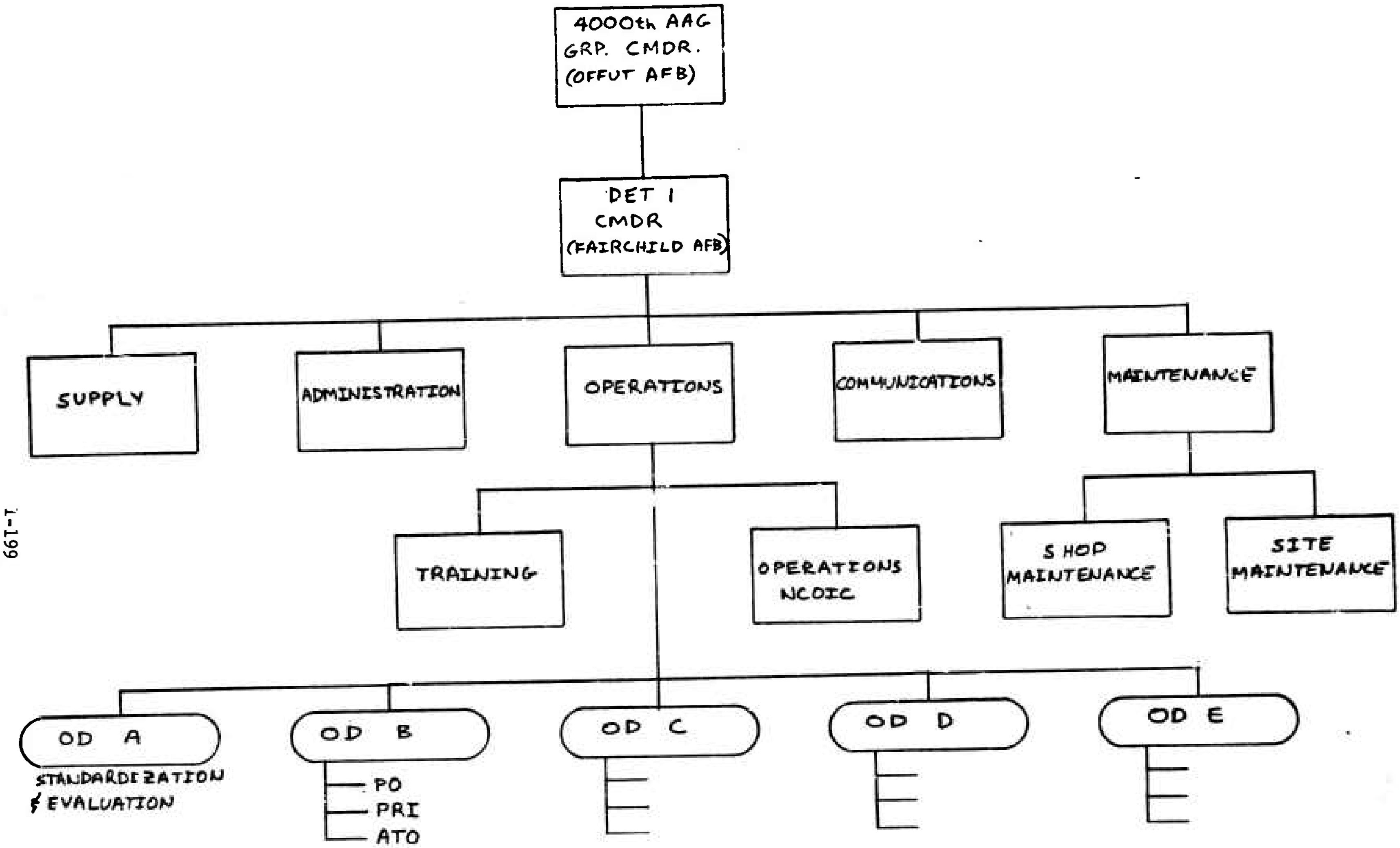
Captain	W. C. Phillips	(Commander)
Smsgt	L. M. Baker	(Senior NCO)
Msgt	R. C. Wands	(Training)
Smsgt	R. M. Sweeney	(Operations)
Msgt	G. M. Sharp	(Supply)
Tsgt	R. G. Debor	(Training)
Tsgt	J. D. Blower	(Training)

Figure 1 shows the organization of Detachment 1.

Operational background is contained in DNSDP-P-057-DRP. During our visit to Detachment 1 we witnessed two runs. The following is a brief scenario of a typical support run.

Pre-Run Set Up

At least 24 hours prior to run, the run schedule is received and validated. About a half hour before the run, the system is configured, recording tapes mounted, and the acq./track paper tape



PO – PROGRAMMER/OPERATOR
PRI – PRIMARY READIN OPERATOR
ATO – ACQUISITION/TRACKING OPERATOR

FIGURE 1 - ORGANIZATION

is selected and readied. The operations officer establishes communication with the CCC and verifies the run schedule (by voice).

Run

The signal source is acquired and tracked either automatically or as directed by the paper tape. Telemetry and user data is read out of the payload on command, as is the user data if required. This data is recorded for post-run transmission to the CCC.

Past Run

Recorded data is transmitted to the CCC. Run execution is reviewed by voice with the CCC. The some cases, runs may overlap, to the extent that a new run may be started during post-run if sufficient recording equipment is available. The acquisition of a new signal source can be accomplished in from 1 to 3 minutes.

The detachment supports from 450-500 runs per month, or 15-17 per day. The station provides 24 hour service, 7 days a week. A run takes from 45 minutes to one hour. Maintenance activities consume about 1.5 hours per day on an average, but may overlap operations to some extent. Training activities are scheduled on a non-interference basis. Captain Phillips indicated that the support requirements can vary greatly, depending upon user requests and could increase in the future. From these estimates, it would appear that additional personnel would not be required to support Phase I of DNSS, if the required support did not exceed 2 to 3 hours per day. There is about 1850 square feet of floor space available for additional equipment at Detachment 1. Whether the location of the station is technologically switchable for early DNSS efforts will have to be determined.

As indicated in D. Potter's trip report, the system is awaiting a major upgrading. Whether the above observations about the site's capability will be valid after the upgrade requires some study. If possible we should get (through SAMSO) any documentation we can concerning the upgrade to help in this accessment.

The remaining comments of this report reflect the current data processing configuration with a few noted exceptions. The processor used is a Data General Supernova with 8k memory, a Sykes Compu-Corder (cassette tape), a Hazeltine 2000 CRT with attached keyboard entry, an ASR 33 TTY, an interface with the payload transmit/receive command loop, a real time clock, and a United Business Systems DS 2400 modem. The data processing system provides support for the following functions:

- Communications with CCC
- Communication with payload
- Real time command/control operation

D. R. Potter
Visit to Detachment 1, SAC 4000th AAG

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After the upgrade, the system will have an additional Supernova with 16k or more memory and a 1.5 megaword disk. The modem will be replaced with a 9600 baud Codex modem. A medium to high speed printer is also planned. Functions added will be antenna control and telemetry processing. The real time clock will be replaced by an Ostron Loran C Model 200C and a Systron Donner Time Code Generator (Model 8155).

We were unable to find out any information regarding the design and implementation of the software for the upgraded system. This information should be obtained through the SPO in order to evaluate support potential for DNSS Phase I.

Owen C. Holzborn
O. C. Holzborn

OCH:lmk

cc: M. Baker
R. Bryan
J. Carroll
G. Hickcox
K. Jutzi
D. Middlebrook
G. Shaparenko
J. Theibault
L. Walters
J. Witherspoon

PHILCO Ford

Intra Company

15 November 1973
DNSDP-P-057-DRP

TO: G. R. Hickcox

FROM: D. R. Potter

SUBJECT: SAC 4000th AAG Visit

On 13 November, S. Langdoc, J. Carroll and D. Potter of Philco-Ford, Newman and Coxey of GDE, Di Palma of Mellonics, Fitzgerald of STI, Captains Prola, Collins, and Sherlock of SAMSO visited the 4000th Aerospace Applications Group at Offutt AFB in Omaha, Nebraska. The 4000th is responsible to SAC for operating a satellite system with a classified mission. A Col. Kirshman is commander of the unit. Majors Pepin, Carroll, and Fitzhugh are responsible for Engineering, Operations, and Computers/Software respectively. Major Burbey was our host and appears to be the senior technical officer. Approximately 225 Airforce people (entirely blue suit) man the Command and Control Center (CCC) at Offutt and the two Command Relay Stations (CRS's), one at Fairchild AFB near Spokane, Washington., the other at Loring AFB, Maine. The system supports three operational satellites in 450 n.m. circular orbits, inclined at 98.7°. The satellites were launched to have ascending node times of 6:30 AM, 8:00 AM and noon local time. Each satellite makes 14.15 revolutions per day, 10 of which are visible to one or both of the ground stations. Thirty satellites, manufactured by RCA, have been used in the program which started in 1963. Radiation Inc. built the station transmitting and receiving equipment. The satellites may be commanded in real time to dump telemetry, dump payload data, change command systems, change attitude control parameters, etc; and must be loaded with stored commands to dump data to remote users, to define vehicle ephemeris to remote users, and to sequence the payload. Because of the size of onboard storage, payload sequencing commands are loaded every 12 hours on rev 0 and rev 7. Ephemeris data is loaded on rev 13 for a 24 hour period. The role of the ground system encompasses the following:

1. Scheduling satellite and ground system operations based on user requests.
2. Commanding the satellite based on approved operation schedules
3. Delivery of payload data to the users.
4. Analysis of vehicle and payload telemetry to determine system health.
5. Maintenance of the system hardware and software.

G. R. Hickcox
SAC 4000th AAG Visit

15 November 1973
DNSDP-P-057-DRP

Current Ground System Configuration

Figure 1 shows the current configuration of the ground system. At the CRS's, uplink communication with the vehicle is on VHF at a 25 bps rate. The FM/FM real time telemetry downlink is on UHF. Payload data is dumped in encrypted form on S-band to the station and then transmitted via wide band directly to the user. The 64 points on real time TM are digitized at the CRS and transmitted over the 2.4K baud line to the CCC. The same 2.4K baud line is used to transmit the command data and other station set up data to the CRS. The satellites are tracked by a 40 ft. dish which is driven by a selected papertype for acquisition, and by autotrack after. An 8K Data General Supernova computer at the CRS supervises command transmission, command verification, TM digitization, and the communications with the CCC. No encryption devices are used in the uplink.

The 16K Supernova at the CCC performs the following functions:

1. Supervision of digital communications with the CRS
2. Support of 5 Hazeltine 2000 alphanumeric displays in the operations center for display of telemetry and transmission of commands.
3. Driving of 2 Sanborn strip chart recorders
4. Supervision of commanding operations

This computer system includes a 256K word disk, a tape drive, printer, card reader, and tape reader/punch. The WWMCCS 6070 computers at SAC head quarters are used in a batch mode to generate daily and weekly scheduling data, the daily pass plans (including message loads), and telemetr predictions orbital elements for each of the vehicles is obtained from the Space Defence Center via TWX. User operations requests are also obtained via TWX input.

System Operations

The basis for all operations is a kind of system operations plan called the Master Listing which contains the following kinds of data:

1. Ephemeris Events such as ascending node times and locations.

2. Station Events such as rise and set times, max elevations, applicable antenna tracking tape,

3. Real time and stored commands to be loaded in the vehicle

4. Telemetry predictions based on commanding and prediction models.

5. Scheduled vehicle and payload operations.

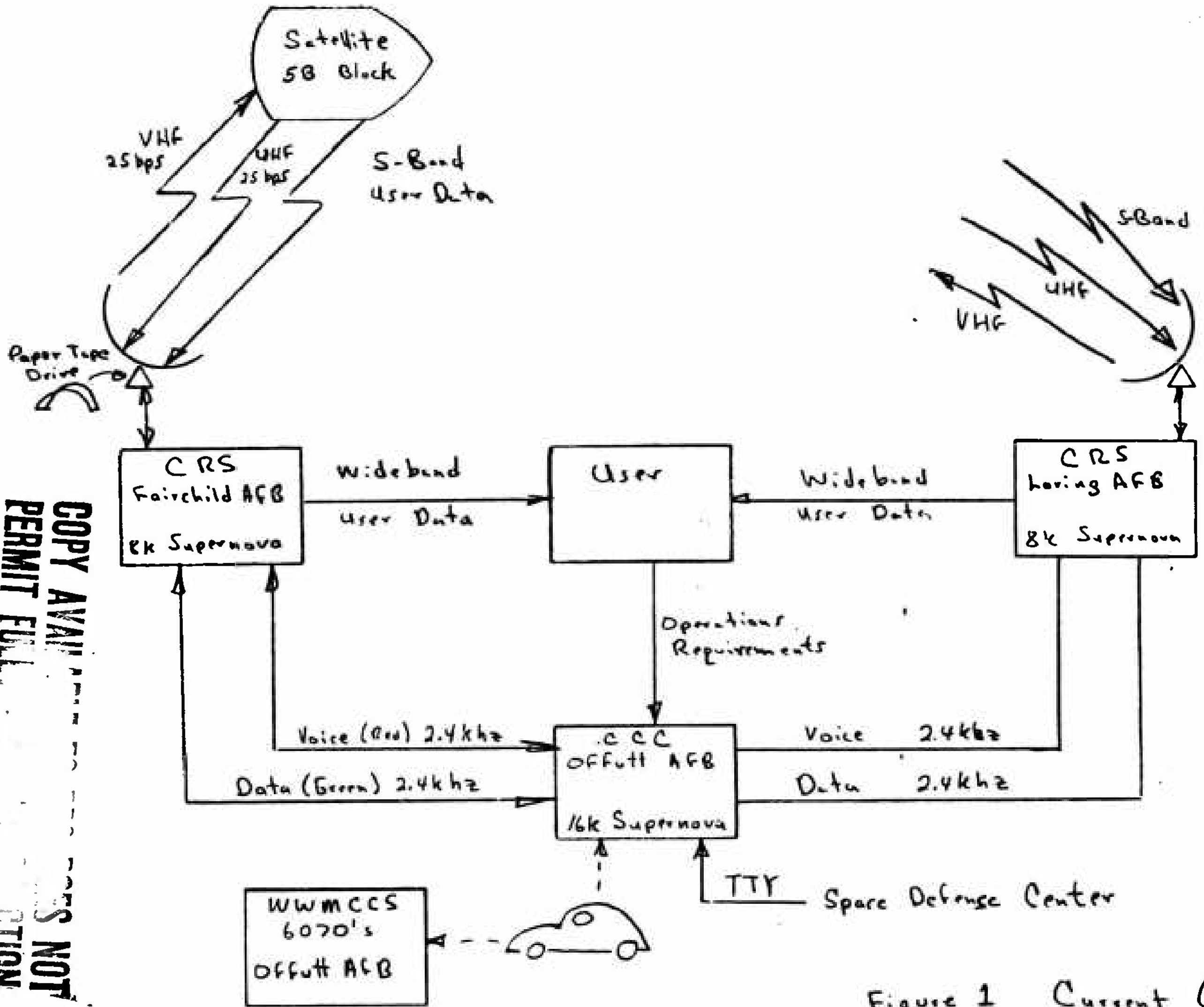

Figure 1 Current Configuration

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Inputs to this plan are generated by a scheduling crew based on user inputs, orbital elements (good to .3 mi. intrack over 3 days) received from Space Defence Center, and past vehicle performance. Input is carried to the WWMCCS 6070, the program executed, and returned to the scheduling crew by computer operations personnel. The scheduling crew is responsible for validating the generated plan. This Master Listing is generated weekly and updated daily. It is used as the basis for all operations control and evaluation by the operations staff. Specific outputs generated during the run, such as the command load and the telemetry predictions, are loaded into the CCC Supernova by computer operations in preparation for pass support. Other outputs, including station rise/set times, tracking tape number, command message data, and station configuration data are sent to the stations 60 hours at a time as a backup against data line CCC failure.

The Operations Control Center at the CCC contains five operating positions, each equipped with a Hazeltine 2000 alphanumeric display. These positions are manned by two teams and a supervisor. A team encompasses a System Controller (officer) and a Data Analyst (noncom). The controller has a keyboard capable of calling up and sending commands and command messages, and is responsible for all operations during the pass. The analyst is responsible for analysis of real time telemetry data and has a Sanborn strip recorder to which he may direct selected telemetry. The supervisor is responsible for the entire crew, and as such monitors operations, resolves conflicts that arise during simultaneous operations, helps with particular problems, and in general supervises and evaluates. Four 5-man crews man the control center on 12 hour shifts. A fifth crew performs a standardization function by operating with each crew once a week to make sure operations are consistent and performance is not becoming sloppy.

A typical pass involves approximately 35 minutes of time. The 15 minutes pre-pass period involves establishing communications with the station, checking out equipment, and discussing the pass plan with the entire crew of the CCC and CRS. The 15 minute pass starts with the controller commanding a real time telemetry dump for 1 minute and a payload data dump. Each real time command sent is verified by an accept/reject monitored at the CRS. If stored commands are to be loaded, a special mode is entered where the entire essage is loaded, then dumped to the CRS and compared with that sent up. During this time, the data analyst is checking the telemetry dump which is compared against the predicts by the CCC Supernova and flagged if out of limits. Near the end of the pass another one minute TM dump is commanded. After fade of the vehicle, an additional 5 minutes is spent summarizing the pass and reconfiguring the equipment.

A simulation/training mode exists in the CCC Supernova software allowing the control center to practice pass operations, respond to anomalous telemetry conditions, etc. Also available in the CCC is a voice recorder monitoring all transactions between the CCC and the CRS's.

G. R. Hickcox
SAC 4000th AAG Visit

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The real time telemetry which is transmitted to the main Supernova in the Operations Control Center at the CCC is also intercepted by a Supernova in the SAC Integrated Data Analysis Facility (SIDAF) in the local engineering department. Manned by seven engineers and 3 technicians on an 8hr/day basis, this group is responsible for post flight analysis of the telemetry data, and when required, of the payload data. The SIDAF equipment includes a 32K Supernova, dual cassette tape recorder, moving head disk, Tektronix Storage Tube and Hard Copy Unit, and a communications interface. A days worth of raw telemetry for each vehicle is accumulated on the disk and stored on a tape cassette. Software in the Supernova provides for analysis of up to 5 weeks of data, including: conversion to engineering units, trend analysis, statistical evaluation, (mean and standard deviation), and plotting and cross plotting. Correlation of the telemetry with the commands is currently not automated, so considerable time is spent poring over listings and data plots.

Planned Upgrade

The system described above is operating the "5B" block of vehicles. The "5D" block of vehicles to be operational by fall of 1975, is a major advancement in vehicle complexity. Among the changes are: on-board computers, three axis stabilization, number of telemetry points increased to 560 from 64, capability to record telemetry on payload recorder, digital telemetry rather than analog, uplink command rate increased to 1000 bps, all communication via s-band. Figure 2 shows how the ground system will be upgraded. All vehicle communications will be SGLS compatible S-band on Channel 2. Real time telemetry will be transmitted at either 2K or 10K bps. Recorded telemetry will be played back with payload data into the ground station. This payload/telemetry data will then be transmitted to the user's facility via an American Satellite Corporation relay satellite. The user's facility strips out the telemetry data and sends it to the CCC via another data link. The data and voice lines from CRS to CCC will be upgraded to 9.6K baud, with voice line acting as back-up for data line and vice versa. Codex modems will be used. The primary computer at the CRS will be upgraded with 32K main memory and 1.65M words disk storage. An 8K Supernova will be included in the antenna drive system to compute antenna drive polynomials from orbit elements sent out from the CCC. Telemetry software in the primary computer will be upgraded to provide for table driven telemetry handling so that the format or local processing can be changed without major modifications. Plans are for report by exception telemetry processing as well as event reporting.

A Software Development/Maintenance Facility will be developed which includes a vehicle simulator so that software for the entire ground system can be developed and tested in a simulated environment.

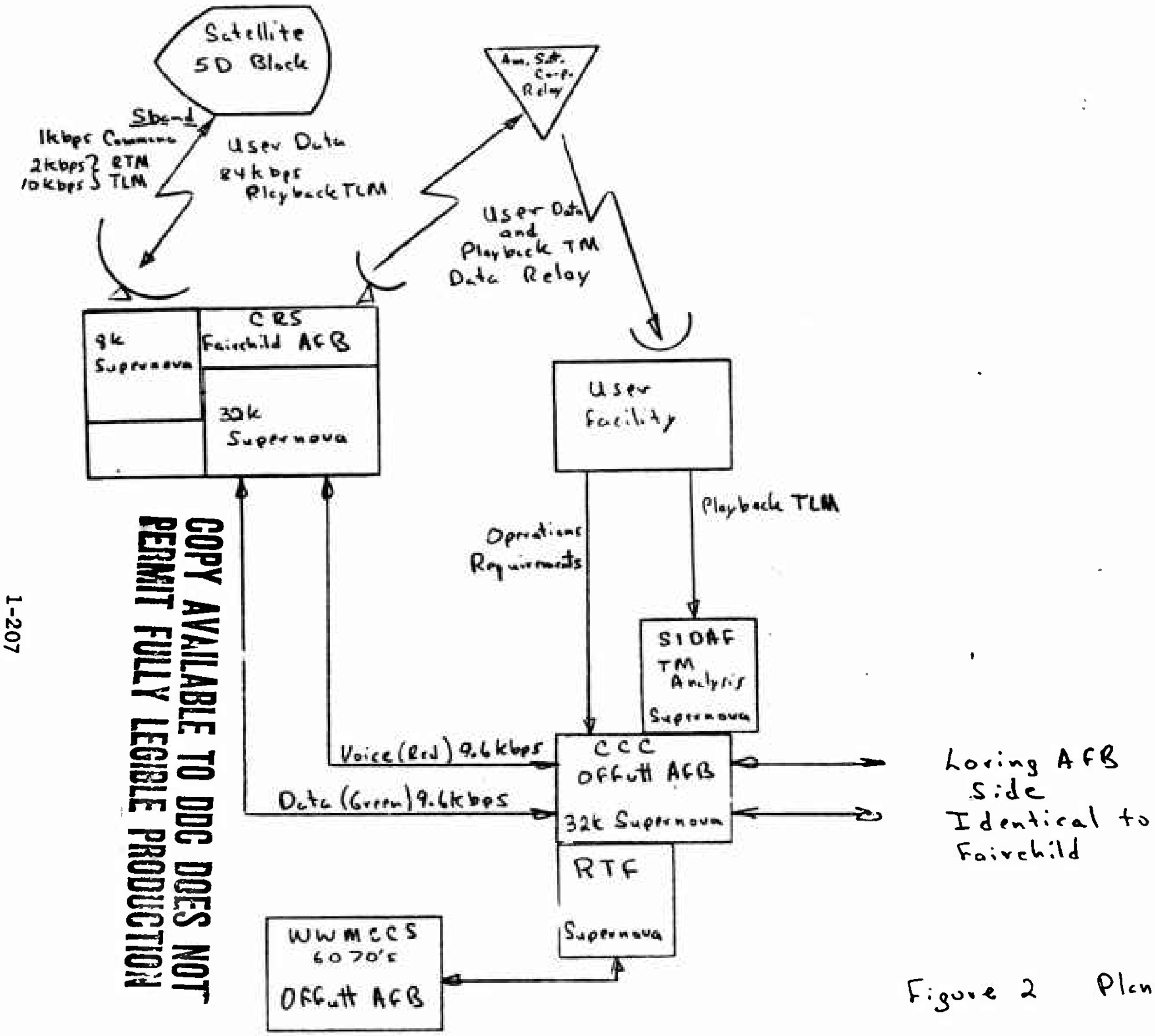


Figure 2 Planned Upgrade (1975)

Communication between the CCC and the WWMCCS computers will be upgraded using the SATIN communications system. A Remote Terminal Facility (RTF) will be installed in the CCC to provide remote terminal input to the 6070's. Initial installation will not alllow direct connection of the RTF to the CCC Supernova for security reasons. Data will come into the RTF, will be scanned for possible classified data by computer operations personnel, and will only then be cleared for input to the Supernova (either on dataline or manually, they were not yet sure). Software developed for the 6070's is being limited to 40K modules to assure getting on easily. The two systems apparently have 256K of memory each.

Ability to Handle DNSS

In relation to expansion for DNSS, Col. Kirshman and his staff provided the following data:

1. There is expansion room at the CRS's (empty buildings) and at the CCC a 30X50 room. Backup power at the CRS's may be a problem since the current generator is sized for their equipment.

2. There are 5 WWMCCS type 6070 machines at SAQ which may have number crunching capacity for an orbit determination task. They were not sure how much was or could be available.

3. They suspected there was no time available on the Univac 1110 machines on the base.

4. They felt that the current CCC operations staff and complex could handle more vehicles without expansion if the number of CRS's remained the same. The main problem would be phasing vehicle passes so that both SAC and DNSS vehicles could be properly serviced. On this subject, Captain Prola will arrange an exchange of orbit element data between SAC and DNSS so that both organizations can study the phasing problem.

5. The antenna feeds at the CRS's can probably not handle more than 1Kw power into the antenna.

6. Hardware configuration documentation is fairly complete and will be requested of the SAC SPO by the DNSDP SPO.

7. Software documentation is probably very sketchy. They do not conform to any specification standards, although they hope to get themselves compatible with JCS publication 7 Chapter 4 sometime in the future. Major Fitzhugh was somewhat embarassed by this question, but wouldn't say anything firm, so it looks like a problem.

G. R. Hickcox
SAC 4000th AAG Visit

15 November 1973
DNSDP-P-057-DRP

Summary

Several problems need not be resolved.

1. The Spokane CRS may not occur early enough in the DNSDP time line to provide optimum command loading timing.

2. Only two remote sites exist or are planned. Thus other arrangements must be made for the other monitors.

3. Large scale computing power may be available, but more investigation needs to be done.

4. The phasing between SAC and DNS satellites must be studied to determine the impact of overlap on DNS operation

5. While the system will apparently handle command loading and telemetry evaluation, more specifics in these areas concerning the upgraded system should be obtained.

D. R. Potter

D. R. Potter, Supervisor
Systems Development Section

DRP:lmk

cc: R. Bryan
J. Carroll
G. Hickcox
O. Holzborn
K. Jutzi
D. Middlebrook
G. Shaparenko
J. Theibault
. Walters
J. Witherspoon
M. Baker

PHILCO Ford

Intra Company

19 November 1973
DNSDP-JTC-032

TO: R. N Bryan

FROM: J. T. Carroll

SUBJECT: SAC 4000th AAG Visit and Det 1 Visit

REFERENCE: a) Ltr J. T. Witherspoon to J. T. Carroll, Same subject, 7 November 1973 DNSDP-JTW-098

b) Ltr D. R. Potter to G. R. Hickcox, SAC 4000th AAG Visit, 15 November 1973, DNSDP-P-057-DRP

1.0 PURPOSE

This trip report supplements reference b), adding some hardware descriptions and describes the hardware configuration at Det 1.

2.0 SAC 4000TH AAG

Attachment A indicates the future SAC system. The American Satellite Corporation will install a one way 1.544 MHz Data link with CRS No. 1 and No. 2 to site III at which time the 240 kHz supergroup will be deleted. The 2400 Hz voice and data line will be upgraded to 9600 bands.

Figure 1 is the anticipated future Command Control configuration to be used to support the block 5D systems.

The WWMCS Honeywell Computers will be connected by land line with the CCC. All personnel in the CCC will have SYOP EBI Clearances and the incoming data continuously monitored at the SPTGP for breach of security.

3.0 ANSWERS TO WDL QUESTIONS

Philco-Ford received the below answers to questions asked the customer.

1. Availability to support DNSS -Fairchild supports around 500 runs/month, LIZA around 400 runs. Average time for each run is 12 minutes, post run is 5 minutes, turnaround is 3 minutes.

No runs currently are made from 1400 to 1700 hours local time. SGLS system is a fixed channel 2 uplink. 1 kW is the maximum transmitter output to a 40' antenna because of feed restrictions. Current transmitters are located at focus in a cage. Cage supports would not hold the weight of a 10 kW transmitter Loading on system is variable because quantity and time of arrival of satellites varies.

2. Computer availability-Mini Super Nova available whenever site is not tracking. WWMCS Honeywell 6070 computers are available providing no more than 40K of memory is used. Global Weather Unival 1108/1110 are not available.

3. 40' antenna gain: 45.9 db, measured 46.5 at 10° Elev., for S Band. Feed limited to 1 kW. Building to house a 10 kW xmitter located 60' from radome. Larger xmitter requires a new emergency generator for sites. S Band Paramp noise temp 100°, measured 91.42, gain 28 db, type Micromega 28-251.

4. Space: 2500 square feet available at offutt 1800 square feet at the CRS's (abandoned mess hall).

5. Crypto: KG 34 (Satellite uses: KG 44).

6. Communications: Simplex 1.5 megabit and duplex 9600 bps lines between CRS and CCC are available whenever other operations are not being conducted.

7. Security: CCC personnel all require SYOP EBI Clearances. Command encryption using KG 34 is possibly scheduled for future installation (may not be implemented). Command authentication is not programmed for future implementation.

8. SGLS Radiation Inc has been contracted to provide a single SGLS Channel 2, 1 kW transmitter at both CRS's. Equipment includes the following:

Timing: VLF Astron. 200C Systron Donner Model 8155

Antenna 45.9 db, 10° elevation, 250°k. Slew rate Az 10°/sec, $5^{\circ}/\mathrm{sec}^2$; Elevation 4°/sec, $5^{\circ}/\mathrm{sec}^2$. Mesh surface with xmitter installed at focus.

Paramp Micromega 28251 100 mHz BW, 28 db gain, 100° k Noise, VSWR 1:5:1 gain stability ± 0.5 db.

S Band Post Amp AM 2200 NL, Gain 31.2 db, Noise 6.8 db.

Receiver RHG Electronics, Noise 8.8 db BW 6.6 MHz.

Directional Coupler Post Amp Englemann Microwave C-403-N Loss 0.24 db

Ranging: None

Refer to Figure 7 for CRS station rack elevation drawings detailing other CRS equipment.

9. Documentation: The DSAP network is exempt from any AF standard documentation or reporting system. Radiation supplied a minimum of documentation for installation and the station has a completed installation test plan. No attempt has been made to recalibrate the equipment or maintain any configuration control as different modifications have been made by DSAP personnel.

10. Availability: Future availability can be predicted only if the current loading remains constant. Three conditions are possible. No change which is the least likely. Saturation of the network by supporting both the 5C and 5D systems or four or five systems until the 5C systems are phased out. This is likely to occur when the network is needed to support DNSS Phase I. The third less likely possibility is phasing out the 5C and 5D systems and use of the more sophisticated NASA GOES system.

Statistical availability data is as follows for 5C systems operating in the present environment:

a.	Turnaround	1.5 minimum min., 3 min. desirable
b.	Run	12 min. average, 15 min. max.
c.	Post Run	4 min. average, 10 min. max.
d.	Runs per month	900; 500 at FAIR, 400 at LIZA
e.	Window	A no operations window occurs between 1400 and 1700 hours
f.	Prerun	15 min. min., 30 min. desired, but not required

11. Configuration: Figure 1 of this report indicates the future configuration of the DSAP network. Attachment A indicates the Overall system configuration and manning. The SPO will make the Radiation proposed configuration details and parameters available to both Contractors.

12. Wide Band Ground Communications: The 5D era communications as shown in Attachment A consists of the following:

1.5 MHz simplex communication provided by CRS site located communication relay stations. Contractor American Satellite Corporation, ASC transmitter ANEC 4 to be installed 4 January 1974. 240K BPS lines to be then abandoned. 6 year contract at $55,840/month. Existing supergroup 240K BPS costs $93,000/month. Above costs are combined costs for both CRS Det no. 1 and no. 2 to Offitt.

Data Communications will be short fixed length messages in realtime and variable length files in none real time. Figure 1 and Attachment A indicated the computers envolved in communications (Supernova).

13. Data and Voice Ground Communications: Two duplex data lines are used for Voice and data. They are interchangeable. A new CODEX 9600C with options 55, 34 and 30 will be installed permitting 9600 land data rates on 3 kHz of bandwidth. Forward error control will be used reducing the effective bit rate some unknown amourt from 9600 BPS. TTY will be SATIN but no plans have been made to use SATIN for the 9600 BPS. SATIN will support 5 and 8 level TTY tapes. The site has direct access to Autobaun, the Offitt AFB telephone exchange and Air Force Secure Voice.

4.0 ANTENNA SIZE

Link analysis indicates that 2 kW is required and 3 kW desired for margin required for the 40' antenna. These figures correlate with the 40' antenna gain at Det 1. The transmitter could be housed in a building 60' from the antenna and brought to the feed by wave guides. Alternately the vehicle receiver could be made more sensitive and the EIRP reduced to allow the 1 kW transmitter to be used.

4.1 SGLS Transmit Channels

The availability of a fixed transmit channel 2 at 1 kW has serious drawbacks for multi-vehicle operation. Multiple channels will be required for the final operational configuration. Single channel operation for Phase I will impose extra care in the design of the vehicle to preclude some of the problems 777 has experienced under similar, multi-vehicle commanding.

The 5D command rate will be 1 kbps.

4.2 SGLS Telemetry Channel

Telemetry will be 50 kbps at launch, and selectable 10 or 84 kbps afterwards for real time or recorded telemetry. Bell and Howell 3700 and 3600 tape recorders are used to record data.

4.3 Antenna Tracking

A separate computer will be installed to store ephemeris data and generate tracking parameters at each CRS.

4.3.2 Antenna Obscura and Radiation Pattern. - Figure 2 indicates FAIR CRS Det 1 antenna obscura. Figure 3 indicates the antenna radiation pattern at S Band frequencies. The antenna will autotrack 3° elevation to 88°. Above 88° up to 17 seconds of data loss will be recorded.

Dr. Fitzgerald indicated a requirement for the customer to perform an RFI site survey.

4.3.3 Antenna Tracking. - A discussion on antenna tracking ensued. The antenna has no anti backlash gearing, nor any accurate digital encoders. A far field tower exists: 400', 3.2^{o} elevation.

4.4 FAIR Station Layout

Figure 4 is the station layout at FAIR and Attachment C are the rack elevation drawings.

4.4.1 Spokane Area. - A map of the city of Spokane is enclosed with the original of this letter. Figure 5 indicates the CRS location, Fairchild AFB and important telephone numbers on base.

4.5 S Band Simulation

The CRS has an S Band signal Simulator, but it will not react dynamically to commanding.

5.0 PREVENTITIVE MAINTENANCE

1½ hours/day envolving three people is the yearly average for preventitive maintenance.

6.0 STATION POWER

Station power available is as follows:

Operations	225 KVA
Radome/Antenna	45 KVA - No problem going to 120 KVA
Backup or emergency Power generator	150 KVA

7.0 SPACE AVAILABLE

1869 square feet is available in the operations area and 200 square feet near the antenna area for installation of DNSS equipment.

8.0 EMP, VULNERABILITY, SURVIVABILITY

None existing or planned

9.0 GROUNDING

25' square mesh with salt field which is kept moist.

10.0 ATTENDEES AT CRS DET 1

Those in attendance at CRS Det 1 (FAIR) are as follows:

Name	Org.	Phone
P. M. Fitzgerald	STI	(415)964-9290
L. M. Baker CMS	Det 1, 4000 (Maint)	247-2805
J. E. Coxey	General Dynamics	(714)279-7301
W. C. Phillips Capt.	Det 1, 4000 (OPS)	247-2805
R. A. DiPulma	Litton-Mellonics	(408)245-0795
H. L. Newman	General Dynamics	(714)279-7301 (X3495)
R. C. Collins Capt.	SAMSO/YEEG	AUTOVON 833-1202
M. Prola Capt.	SAMSO/YEEG	833-1202
O. C. Holzborn	Philco-Ford	(415)326-4350 (X4020)
J. T. Carroll	Philco-Ford	326-4350 (X4346)
R. C. Wands Msgt.	Det 1, 4000 (TRN)	247-2805
R. M. Sweeney Smsgt.	Det 1, 4000 (OPS)	247-2805
R. G. Debor Tsgt	Det 1, 4000 (TRN)	247-2805
J. D. Blower Tsgt.	Det 1, 4000 (TRN)	247-2805
G. M. Sharp Msgt.	Det 1, 4000 (SUPPLY)	247-2805

11.0 TEST EQUIPMENT

Figure 6 lists the 4000 AMG Test Equipment.

12.0 VISIT TO OFFUTT

Reference (b) describes most of the offutt visit. The Agenda was as follows:

AGENDA

13 November 1973

0800	Visitors Arrive	Major Burbey
0815	Visitor Briefing	Major Burbey
0830	Command Briefing	Colonel Kirschman
0930	Tour Facility	Captain Bowers (DO), Major Fitzhugh (AD), Lieutenant Hansen (LG), and Major Pepin (EN)
1030	Engineering Briefing	Major Pepin
1130	Lunch	
1300*	General Discussion	

* Separate discussions available on request.

12.1 Offutt Area

Enclosed with the original to this letter are maps of Offitt Air Force Base and the city of Omaha.

13.0 VANDENBERG BLOCK 5D SUPPORT

WDL will m[illegible]fy VTS to support Block 5D systems as described in Figures 8 9 and 10.

14.0 SUMMARY

SAC 4000th AAG could provide limited DNSS support from two CONUS sites which would require supplemental support from other sites. The SGLS installation would require replacement with a tuneable transmitter, upgrading from 1 to 3 kW or else dictate a new satellite receiver gain parameter. Power in excess of 1 kW would be an expensive modification. Severe station loading may occur during the 5C/5D system phase over. Future station loading is unknown. Space for new equipment is limited and requires new air conditioning. Communications costs would include linking Offitt with sites other than Det no. 1 and 2.

JT Carroll

J. T. Carroll

/da

cc: G. R. Hickcox, J. Theibault, J. T. Witherspoon, D. Potter, G. Shaparenko, D. Middlebrook

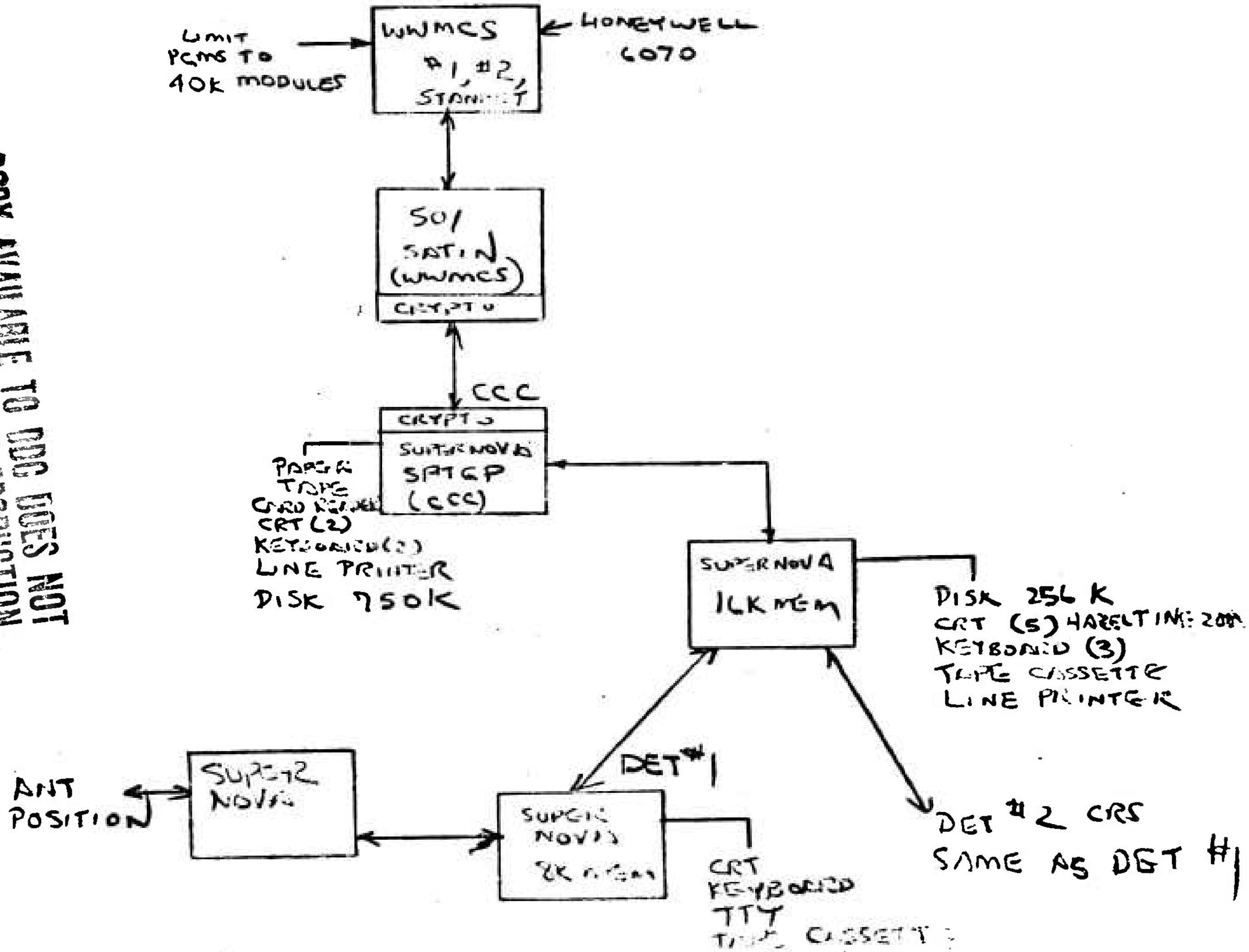


FIGURE 1 5D SYSTEM CONFIGURATION

F-07 3 JAN 63

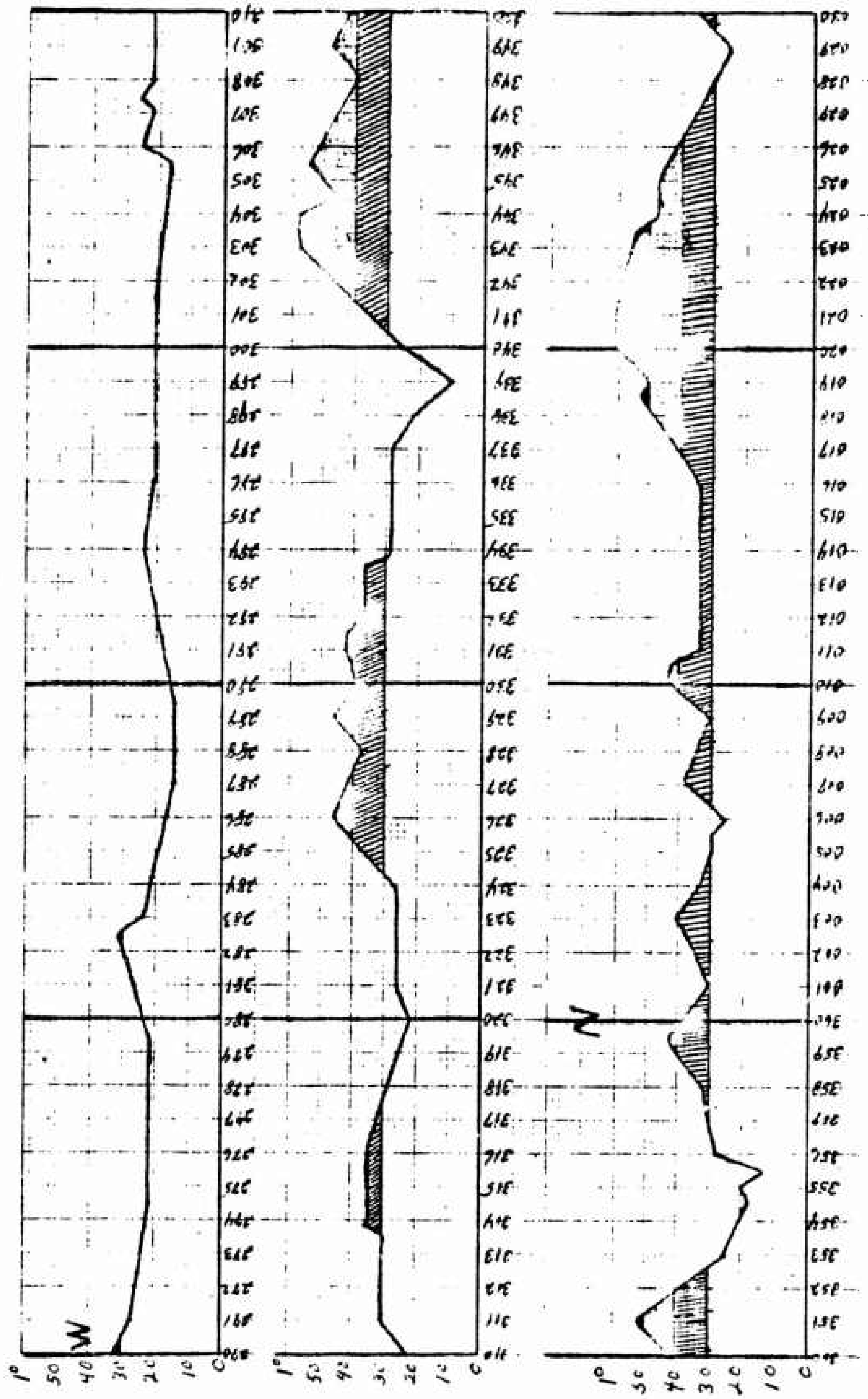


FIGURE 2 FAIR. ANTENNA

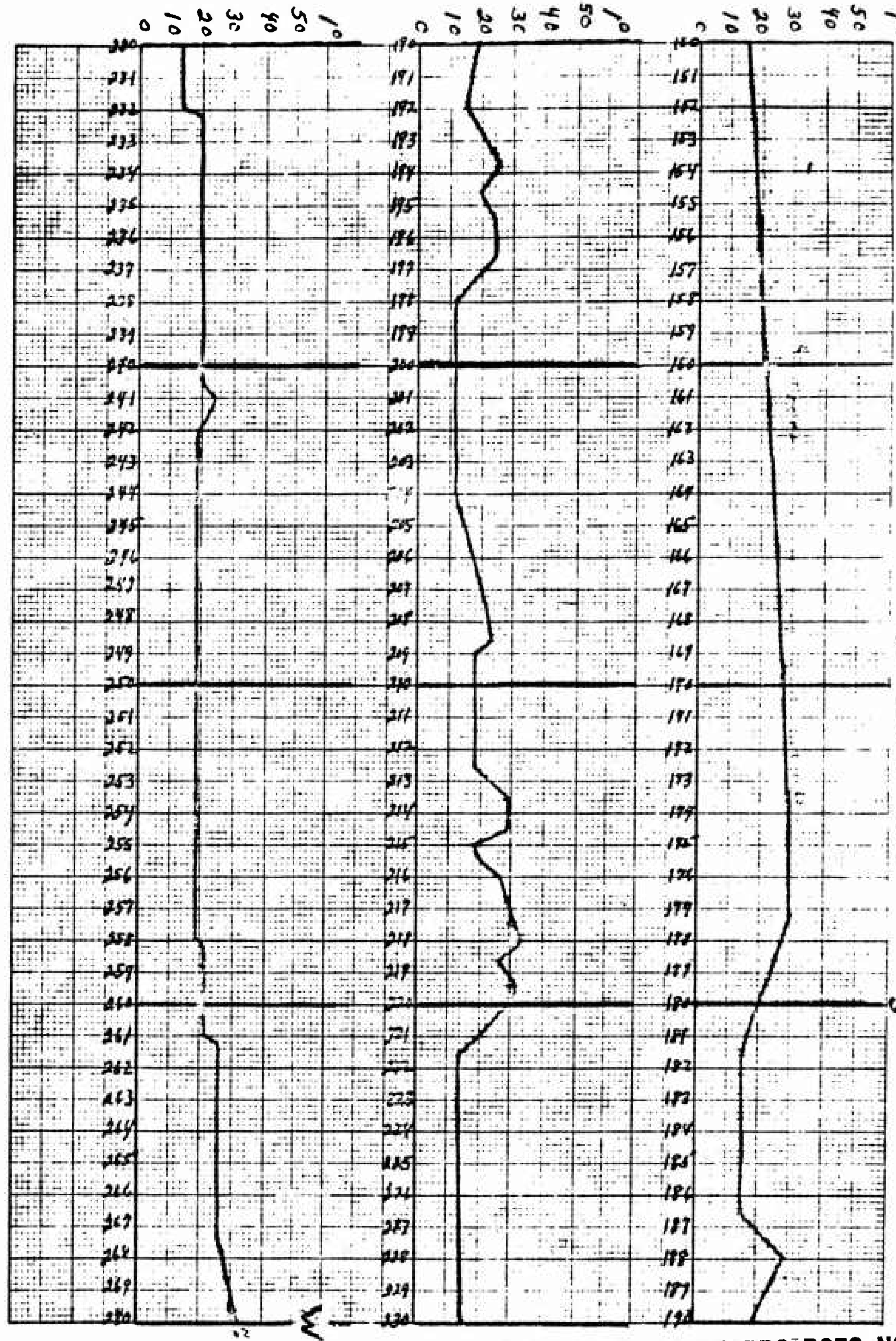


FIG 2 (Con't)

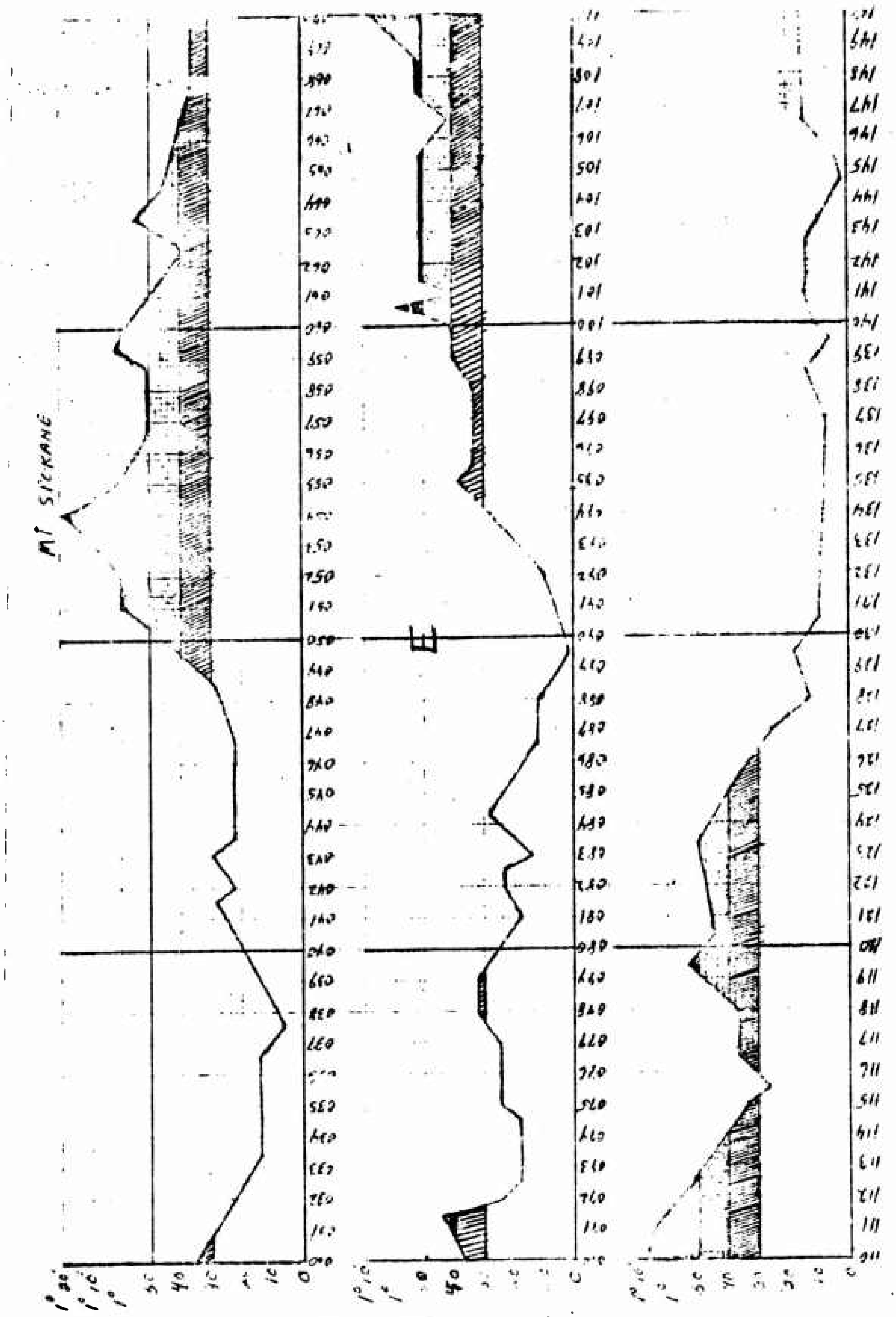
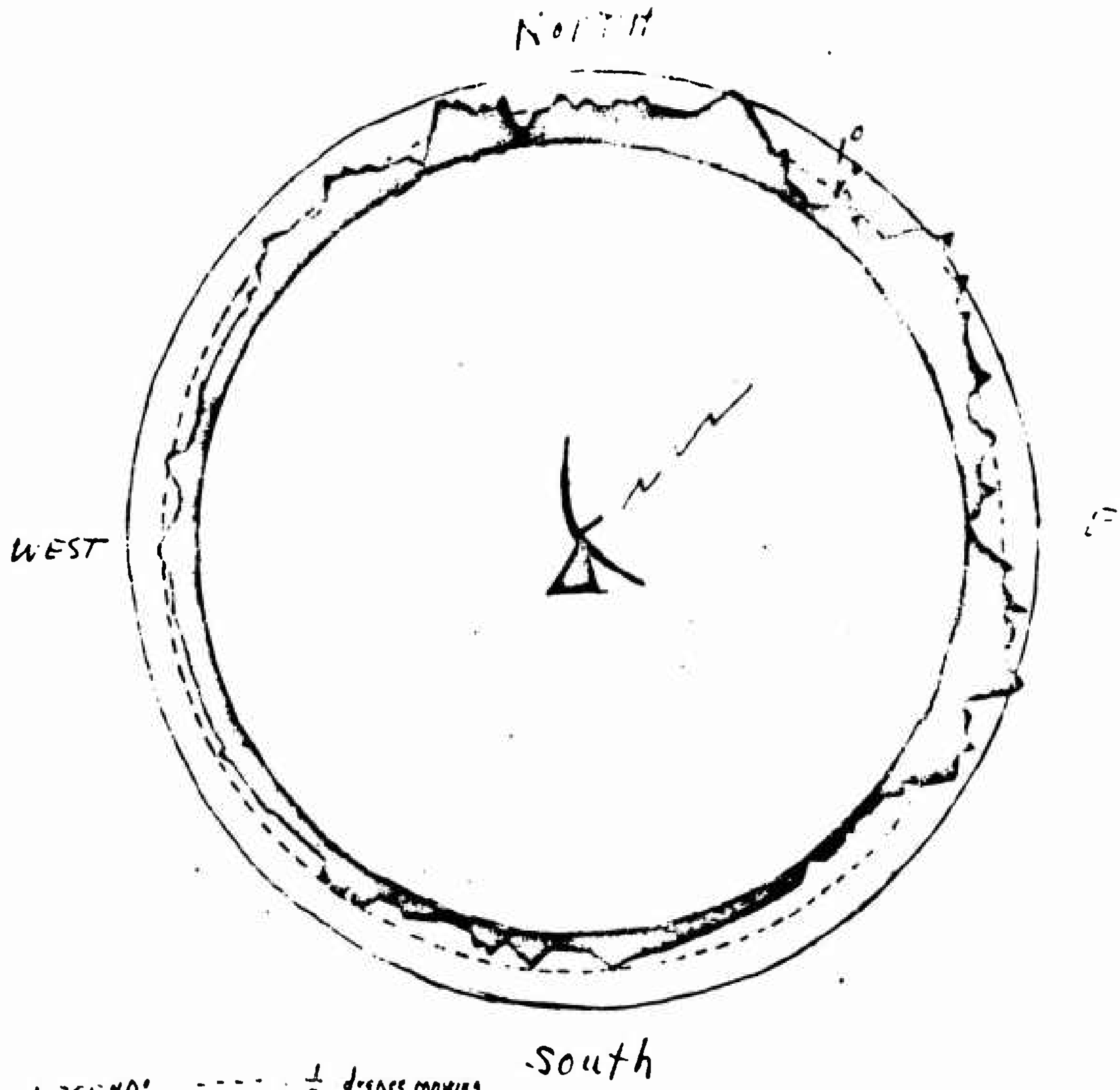


Fig 2 (Con't)



LEGEND: - - - - $\frac{1}{2}$ degree masking

——— = 1 degree masking

FIG 2 (Con't)

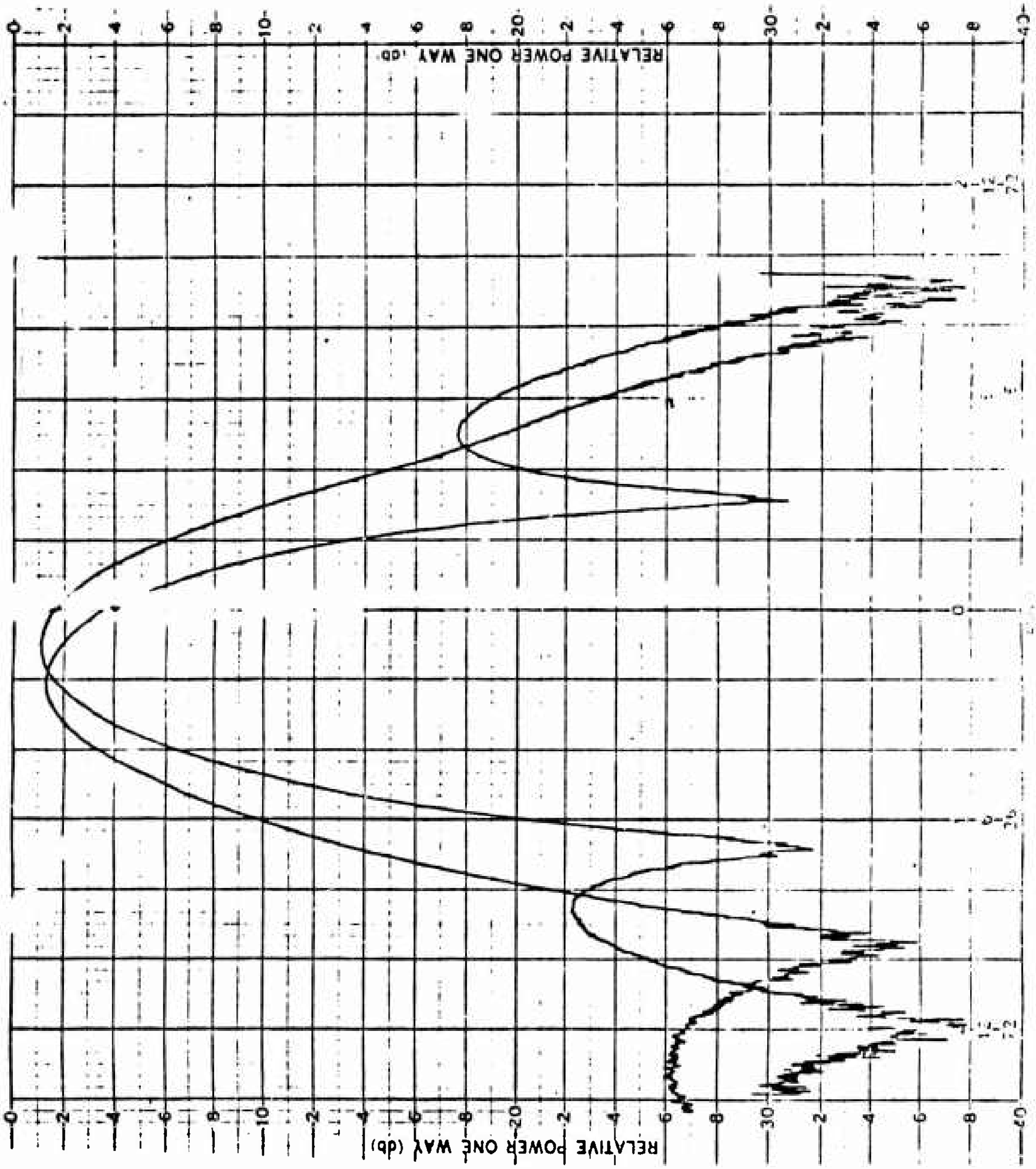


FIGURE 3 S-BAND ANTENNA RADIATION PATTERN

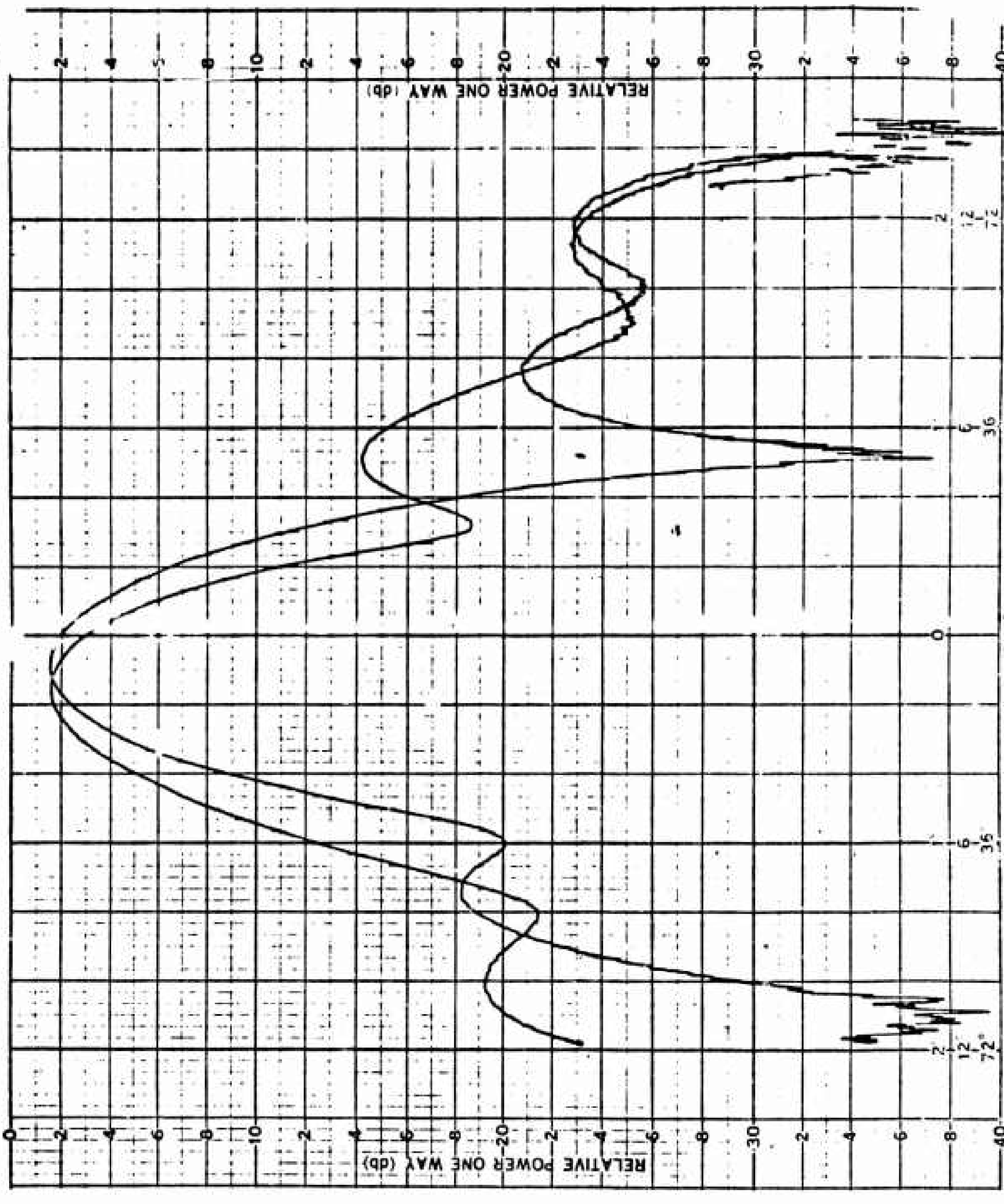


FIGURE 3 (Con't)

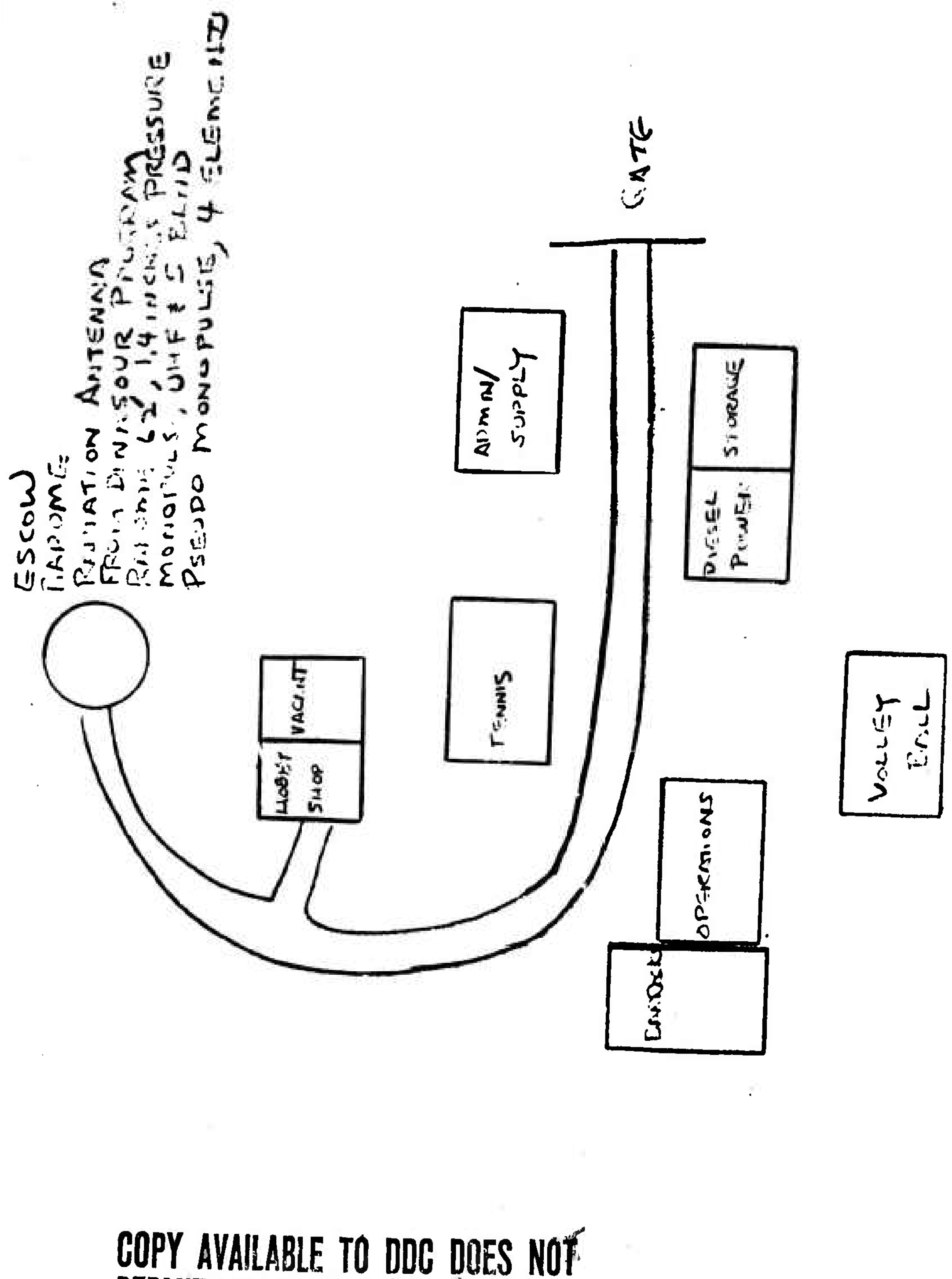
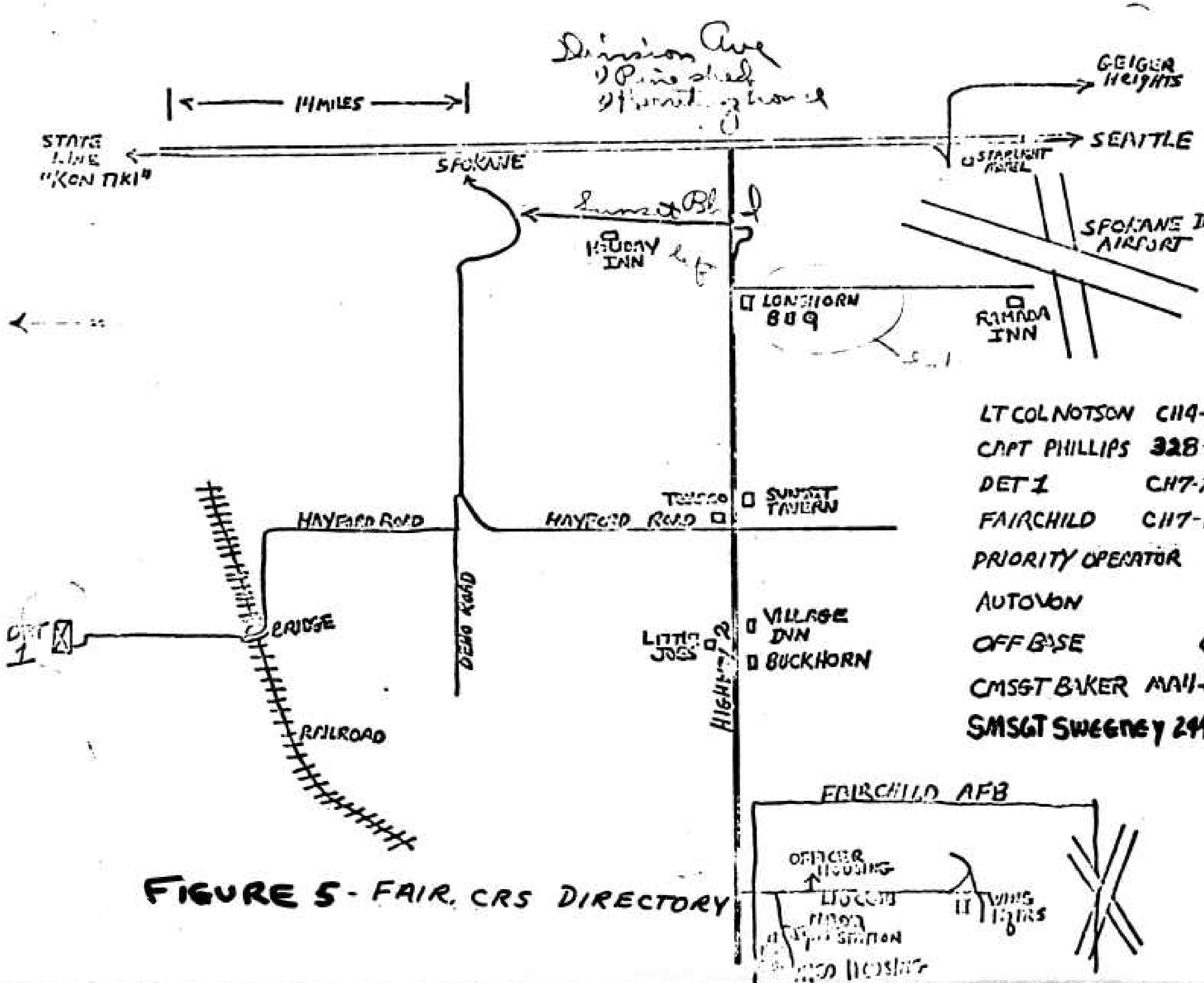


FIGURE 4DE1 #1 CRS STATION LAYOUT



LT COL NOTSON C114-3965
CAPT PHILLIPS 328-6022
DET 1 CH7-2605
FAIRCHILD CH7-1212
PRIORITY OPERATOR (6)
AUTOVON (8)
OFF BASE (9)
CMSGT BAKER MA11-0335
SMSGT SWEENEY 244-2481

FIGURE 5 - FAIR. CRS DIRECTORY

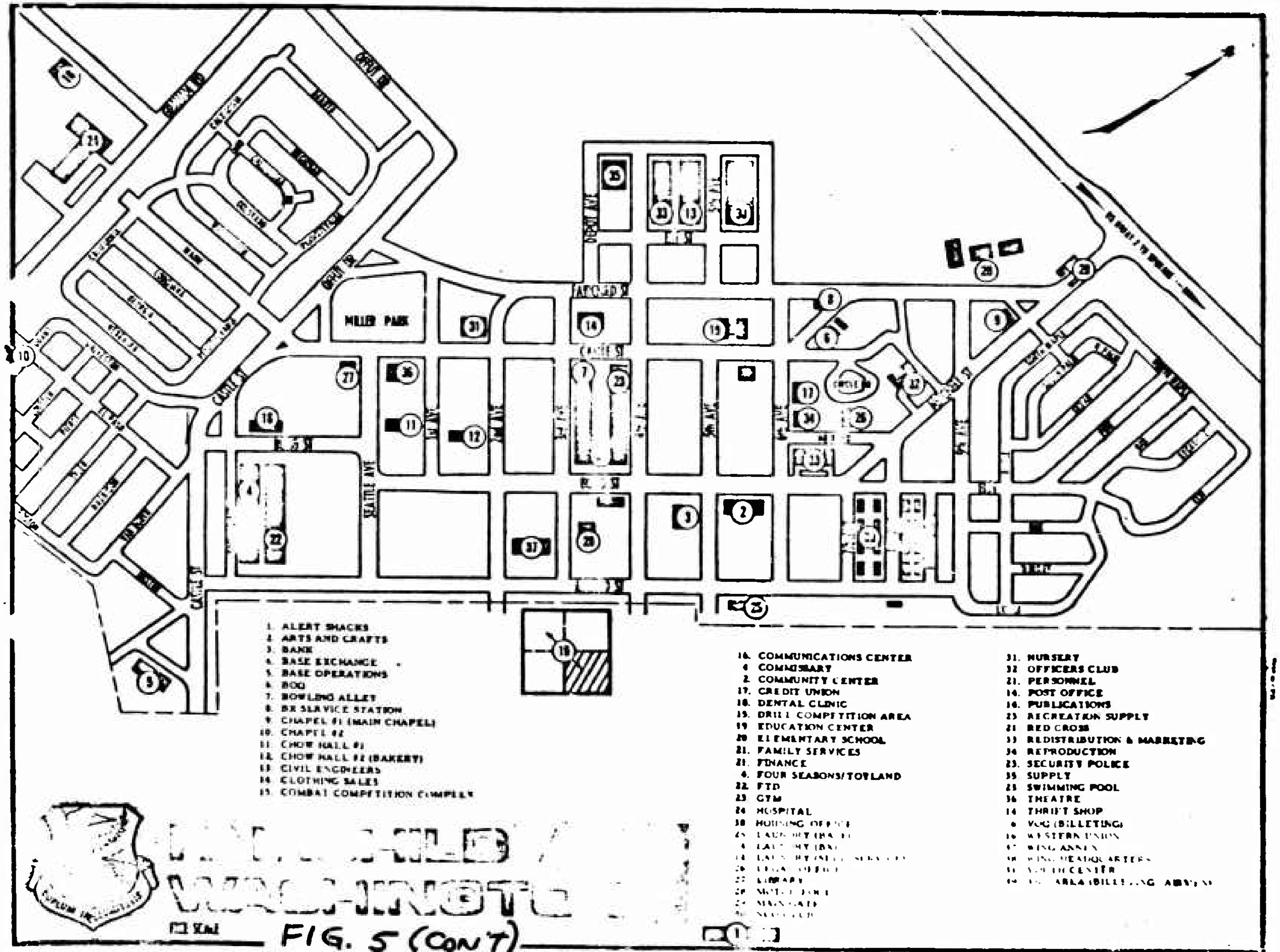


FIG. 5 (CONT)

COPY AVAILABLE TO DDC DOES NOT PERMIT FULLY LEGIBLE PRODUCTION

WELCOME TO FAIRCHILD AFB

Telephone (509) 247-1212

Autovon 352-xxxx

Autovon Operator Asst 352-1110

QUICK REFERENCE PHONE NUMBERS

Division Commander	
Wing Commander	2124
Base Commander	2113
Air Police	5493
Autovon	8
Autovon (Priority)	6
Base Exchange	CU4-2832
Base Operations Dispatch	5435/5439
Base Operations Officer	5481
Base Locator	2357
Base Taxi	2244
Billeting Office	2307
Command Post	21[illegible]1
[illegible] 24; 42ARRSq	2207
D[illegible]	5363
Dining Hall #1	5346
Flight Surgeon	52[illegible]
Flying Safety	5145
Inflight Kitchen	5140
Information	Operator
Job Control	5906
Logistics	5112
NCO Open Mess	CU4-3622
Officers Open Mess	CH4-3044
Personal Equipment	22[illegible]0
Physiological Training	5406
Survival School	2366
Theater	[illegible]
Town Crier (Current Base Happenings)	CH4-2230
[illegible] Alert	5973
Weather Forecaster	5514

NOTE: To call Spokane (seven digit) numbers from on base, first dial 9. To call [illegible] four [illegible] number from Spokane first dial 247.

OPERATING HOURS

BASE EXCHANGE	1000-2000 Mon-Tue-Wed-Thur-Fri
Sat.	0900-1800
Sun.	1000-1700
CAFETERIA	0700-1900 Mon-Fri
	0800-1500 Sat/0800-1300 Sun
BASE OPS SNACK BAR	24 Hours Daily
BOWLING ALLEY	1100-2300 Mon Thur Fri
	0900-2300 Tue-Wed-Sat
	1200-2300 Sun
DINING HALL #1	
Breakfast	0600-0800 Mon-Fri
Breakfast	0700-0830 Sat-Sun
Lunch	1100-1300 Mon-Fri
Lunch	1100-1230 Sat-Sun
Dinner	1500-1800 Mon-Fri
Dinner	1600-1730 Sat-Sun
Midnight Chow	2100-[illegible]100 Daily
CO CLUB . . Dining Room:	
Monday thru Thursday	0700-1000 1100-1300 17[illegible]-2130
Friday	0700-1000 1100-1300 17[illegible]-2230
Saturday	[illegible]0-2200
Sunday	[illegible]0-2100
Main Bar:	
Monday thru Thursday	1630-2400
Friday	1630-0200
Saturday	1300-0200
Sunday	1200-2400
OFFICER'S CLUB	
Breakfast Service:	7 AM-9 AM Mon-Fri
	8 AM-1 PM Saturdays
	AM-1 PM Sundays
Lunch Service:	11:30 AM-1 PM Mon-Fri
	AM-1 PM Sundays Brunch only
Dinner Service:	[illegible] Saturday thru Thursday
	Fri [illegible]
Bar Service:	5 PM-11 PM Mon-Thur, Fri.-Sat 1 AM

FIG 5 (CONT)

EAD

EQUIPMENT ALLOWANCE DOCUMENT

S/N	NOUN	P/N	SOURCE	ERRC	LOCATION SITE 1	2	5
3610ND203033FBM	PUNCH AND BINDING	212PB	FFY	NF2	1	1	1
39202021279	TRUCK HAND	MILT16549	S9G	NF2	1	1	
39202221071	CART HAND 4 WHEEL		S9G	NF2			1
4310ND211034FBM	COMPRESSOR	V50264-6-63			1	1	
58209781000	POWER SUPPLY	LA50-03BM	FHZ	XD2	2		
58359695771ZU	DEGAUSSER	TD2903-4A	FHZ	NF2	1	1	1
5840ND201756FBM	UHF PARAMP	WA395-405	FFY	ND2	1	1	
5840ND206042FBM	CHART PAPER SCANNER	ES64-826-1	FFY	ND2	1	1	
59859140166	COUPLER DIRECTION	777D	S9E	NF2	1	1	
59859571860	ATTENUATOR	355D	S9E	NF2	1	1	
59859931377	ATTENUATOR	355C	S9E	NF2	2	1	
6130ND203121FBM	POWER SUPPLY	TR36-4M	FFY			1	
61300139004	POWER SUPPLY	LA40-05B	FPZ	NF2			1
61304023969	POWER SUPPLY	LK351FM	FPZ	XF2	1		
61308158430	POWER SUPPLY	LH121FM	FPZ	ND2			1
61309421103	POWER SUPPLY	LH122AFM	FPZ	XD2			1
6625ND214577FBM	MODULE TEST SET	B7-45	FFY	ND2	1	1	
6625ND215794FBM	PLUG IN	1821A	FFY	ND2			1
6625ND217100FBM	ATTENUATOR	1151-1	FFY	NF2	1	1	
66250109845	FUNCTION GENERATOR	110	FPZ	ND2		1	2
66250132630	VOLTMETER	3440A	FPZ	ND2	1	1	2

FIGURE 6 EQUIPMENT ALLOWANCE

S/N	NOUN	P/N	SOURCE	ERRC	LOCATION SITE 1	2	5
66250178669	VOLTMETER	125B	FPZ	ND2	1		
66250459895	OSCILLOSCOPE	RM504	FPZ	XD2			1
66250512899	PLUG IN	3A74	FPZ	ND2	1	1	1
66250521506	UNIVERTER	207H	FPZ	ND2	1		
66250634492	GENERATOR	HD1A	FPZ	ND2	1		
66250668519	METER	415D	FPZ	ND2	1		
66250687175	ANALYZER	310A	FPZ	ND2	1	2	1
66250701490YA	CONVERTER	5254B	FPZ	ND2	1	1	
66250718965	PLUG IN	3444A	FPZ	ND2	1		1
66250760806	PROBE	456A	FPZ	ND2	1	1	
66250867165	GENERATOR	900B	FPZ	ND2	1	1	
66250896637	VHF OSCILLATOR	3200B	FPZ	ND2	1		
66251098267	PREAMPLIFIER	1A7A	FPZ	ND2	1	1	
66251136351YA	PLUG IN SWEEP OSC	8692A01	FPZ	NF2	2	2	
66251202196YA	DOLLY SCOPE	200-1	FPZ	NF2			1
66251334631	PLUG IN DUAL TRACE	1A2	FPZ	ND2			1
66251496301	METER	260	FPZ	NF2	2	3	2
66251679863YA	OSCILLOSCOPE	454	FPZ	ND2	1	1	1
66251680503	VOLTMETER	1604M	FPZ	ND2	1	1	
66251792651	SINE WAVE OSCILLATOR	F321A	FPZ	ND2			1
66252255025	RANGE SELECT	3442A	FPZ	ND2	1	1	1
66252263483	PLUG IN	5253B	FPZ	ND2	1	1	
66252474461	PLUG IN UNIT	3B3	FPZ	ND2	2	2	1

FIG 6 (Con't)

S/N	NOUN	P/N	SOURCE	[illegible]	SITE 1	SITE 2	SITE 5
66252481255	PLUG IN	2B67	FPZ	ND2			1
66253024739	DETECTOR	417A	FPZ	ND2	1	1	
66253392046	OSCILLATOR	ANPRM10	FPZ	ND2	1	1	
66253560314	SLOTTED LINE	805A	FPZ	ND2	1		
66253602493	VOLTMETER	410B	FPZ	ND2	2	1	1
66254202379	OSCILLOSCOPE	564B	FPZ	ND2			1
66254411993	VOLTMETER DIFF	85[illegible]R	FPZ	XD2			1
66254423470	OSCILLATOR SWEEP	8690B01	FPZ	ND2	1	1	
66254423585YA	VOLTMETER RMS	323-07	FPZ	ND2			1
66254637141	LOGIC COMPARATOR KT	5010A	FPZ	NF2	1	1	1
66254660586YA	FUNCTION GEN	3310A	FPZ	ND2	1	2	1
66255184659	OSCILLATOR	200CD	FPZ	ND2	1		1
66255183776					1		
66255578261	VOLTMETER	400H	FPZ	ND2			1
66256009164	PREAMPLIFIER	MODEL G	FPZ	ND2	1	1	
66256013874	TESTER TRANSISTOR	KT1	FPZ	ND2			1
66256083558	DOLLY OSCILLOSCOPE				3		
66256155143	VIDEO AMP	526A	FPZ	ND2	1		
66256431670	VOLTMETER				2		
66256434319	BRIDGE	803A	FPZ	ND2	1	1	
66256492032	FUNCTION GEN	202A	FPZ	ND2	1	1	
66256495070	WATTMETER	43	FPZ	ND2	1	1	
66256495262	SIGNAL GEN	608D	FPZ	ND2	1	1	
66256786637	PREAMPLIFIER	MODEL CA	FPZ	ND2	3	2	
66256796508	DOLLY TEST EQUIP	500-53A	FPZ	ND2		2	

FIG 6 (Con't)

S/N	NOUN	P/N		SOURCE	ERRC	LOCATION SITE 1	2	5
66758576796	SCALE GERBER	TP00720BB		S9G	NF2			2
6720ND203066FBM	ADAPTER	10350A		FFY	ND2		1	
6720ND210204FBM	CAMERA	100		FFY	NF2	1	1	
67208632353	CAMERA OSCILSCPE	196A		JSC	NF2	1	1	1
6910ND211070FBM	BK 2 PROTOTYPE	NPN		FFY	ND2			1
79102053400	CLEANER VACUUM					1	1	
6625ND	LOGIC COMPARATOR KT	5011T	[illegible]	FFY	[illegible]			1
6625ND	TESTMOBILE	1119D	[illegible]	FFY	[illegible]			1
6625ND	OSCILLOSCOPE	184A	[illegible]	FFY	[illegible]			1
6625ND	AMPLIFIER	1805A	[illegible]	FFY	[illegible]			1
6625[illegible]027 8244	TIME BASE	1825A	[illegible]	FFY	[illegible]			1
58359865985CI	DEGAUSSER	SE10				1		
	DEVIATION METER	LA71					1	
	DISCRIMINATOR	189F					1	
66255399937	BOLOMETER	476A		JCS	NF2		1	
66258495694	TUBE TESTER	TV2/CU		FPZ	ND2		1	
66259957668	POWER SUPPLY	6224B		FPZ	ND2		1	
6625ND	DIGITAL MULTIMETER	245	DATA PRECISION	FFY	NF2			2

FIG 6 (Con't)

S/N	NOUN	P/N	SOURCE	ERRC	LOCATION SITE 1	2	5
66256889985KH	ELECTRONIC COUNTER	5232A	FLZ	ND2		1	
66250916529	TESTER CURVE TRACE	575A	FPZ	ND2	1	1	
66257081950	TESTER	TV2BU	FPZ	ND2	1		
66257143992	OSCILLOSCOPE	545A	FPZ	ND2	1	1	
66257202926	FREQUENCY METER	LA70A	FPZ	ND2	1	1	
66257221694	ANALYZER SPEC	1L20	FPZ	ND2	1	1	
66257274706YA	VOLTMETER	3400A	FPZ	ND2	1	2	
66257383065	PREAMPLIFIER	MODEL H	FPZ	ND2	2	1	
66257532114	DIFFERENTIAL VOLTMETER	801B	FPZ	ND2	1	1	
66257920549	GUAGE	12-902	FPZ	NF2	1	1	1
66257931344	NOISE SOURCE	343A	FPZ	NF2	2		
66257931348	ELECT COUNTER	524C	FPZ	ND2	1		
66257597616	STROBOSCOPE	1531A	FPZ	ND2			1
66257997956	OSCILLOSCOPE	535A	FPZ	ND2	2	1	
66258134396YA	ATTENUATOR FIXED	AS5	FPZ	NF2	1	2	
66258169338	UNIVERTER	207H	FPZ	ND2	1		
66258190472YA	GENERATOR	606A	FPZ	ND2	1		
66258265824	FREQUENCY METER	N410A	FPZ	ND2	1	1	
66258276225	OSCILLOSCOPE	1805	FPZ	NF2			1
66258514403	POWER METER	430CR	FPZ	ND2	1	1	
66258574352	SIG GEN VHF	608E	FPZ	ND2	1		
6625801/4057	[illegible]		FIL	ND2	1		

FIG 6 (cont)

S/N	NOUN	P/N	SOURCE	ERRC	SITE 1	SITE 2	SITE 5
66258861955	MOUNT THERMISTOR	478A	FPZ	NF2	1	1	
66258919201EW	GENERATOR	8614A		ND2	1		
66258925263	METER	TS2082AU	FPZ	ND2		1	
66258925286	METER	342A	FPZ	ND2	1		
66259119961	REFLECTOMETER	B15-140A	FPZ	ND2	1	1	
66259123773	MULTIMETER	PM7	FPZ	NF2	1		
66259127711	ANALYZER	331A			1	1	
66259280364	SWEEP GENERATOR	8630A	FPZ	ND2	2		
66259308215YA	GENERATOR	222A	FPZ	ND2	1	1	
66259374961	OSCILLATOR	651B	FPZ	ND2	1	1	
66259515955	MULTIMETER (1 REQ)	633VA1	FPZ	ND2	1	1	
66259538219	SIGNAL GEN	202J	FPZ	ND2	1		
66259658241	PLUG IN DUAL TRACE	3A3	FPZ	ND2	1	1	1
66259670460	PLUG IN	5262A	FPZ	ND2			1
66259721459	ELECTRONIC COUNTER	5532A	FPZ	ND2			1
66259734837	ELECTRONIC COUNTER	5245L	FPZ	ND2	2	2	1
66259866361	SCANNER 16IN	S2	FPZ	ND2			2
66259882583	AMPLIFIER	3A6	FPZ	ND2	1	1	1
66259882768	DOLLY SCOPE	201-2	FPZ	NF2			1
66259933389	TEST SET TRANSISTOR	1890M	FPZ	ND2		1	
66259938843	METER SWR	415E	FPZ	ND2	1	1	
66259983407	PLUG IN DIFF COMP	3A7	FPZ	ND2	1		
~~6650ND210739PBM~~	~~MICROSCOPE~~	~~70266~~	~~FFY~~	~~NF2~~			
66756911786	SCALE VARIABLE	TP007100B	89G	NF2			5

FIG 6 (Con't)

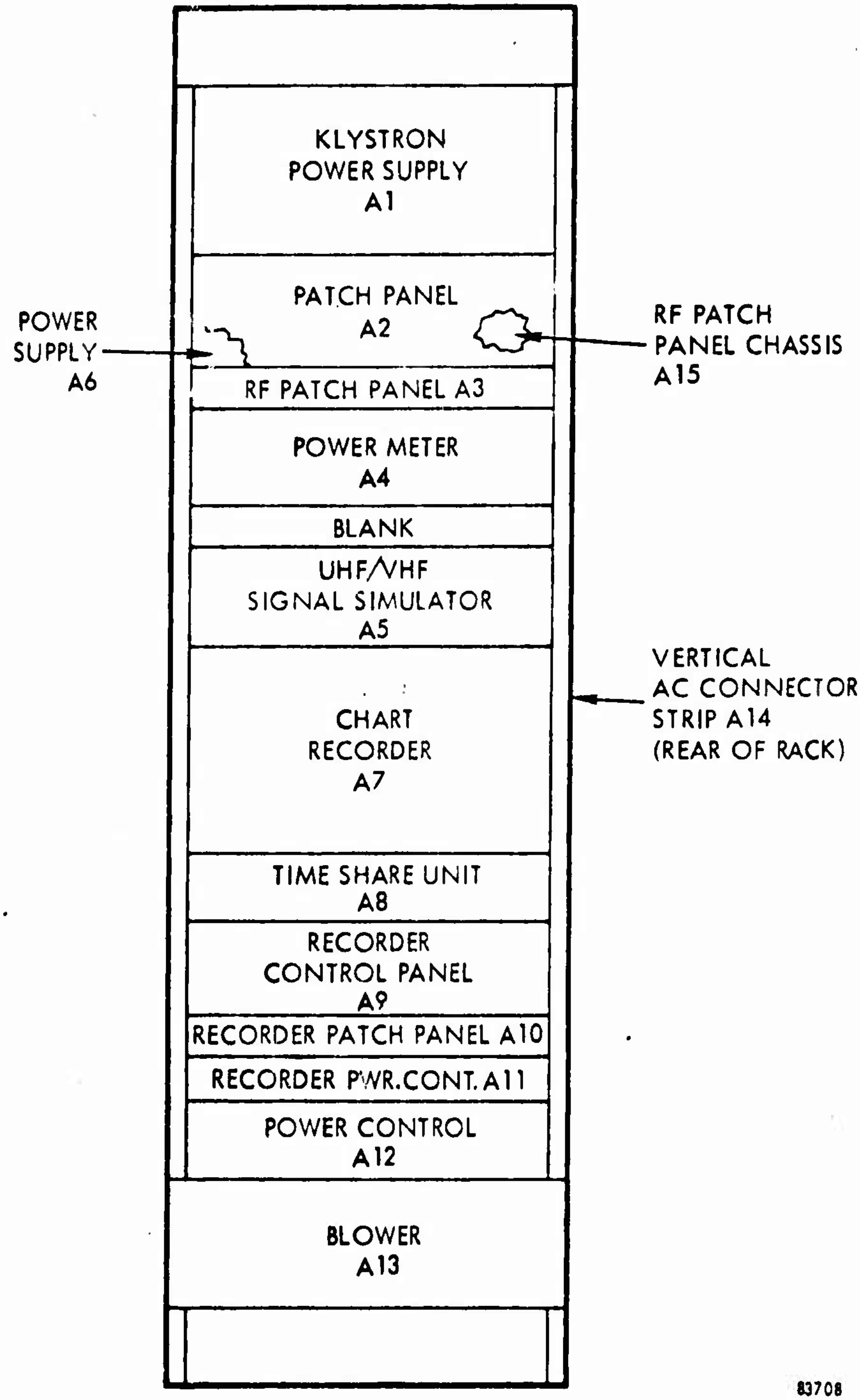
Part No.	Noun	Quantity	Part No.	Noun	Quantity
P6022	High Current Probe	1			
			LK352-FM	Regulated Pow Supply	1
W5M	Variac	1	LK362-FM	Regulated Pow Supply	1
11044A	Voltage Divider	1	I-48-B	Megometer	1
			5010 A	Logic Troubleshooting Kit	1
134	Current Amplifier	1	431B	Power Meter	1
			N6284A	Thermistor Mount	1
3500	Band Pass Filter	1	LA20-05BM	Regulated Pow Supply	1
405CR	DC Digital Volt Meter	1	LA20-05B	Regulated Pow Supply	1
			204B	Tunnel Detector	2
			204B1	Tunnel Detector	1
50-20	Fixed Attenuator	1			
525A	Frequency Converter	1	6201A	DC Power Supply	1
525B	Frequency Converter	1	260	High Voltage Probe	1
7170R	Eput Counter	1	388	Termometer	1
752A	Tube tester	1	603581G1	IF Test Amplifier	1
			3000-30	DIRECTIONAL COUPLER	1
			DC-13	COAX. DIRECTIONAL COUPLER	1
			3000-20	COAX DIRECTIONAL COUPLER	2

FIG 6 (Con't)

Future Test Equipment requirement

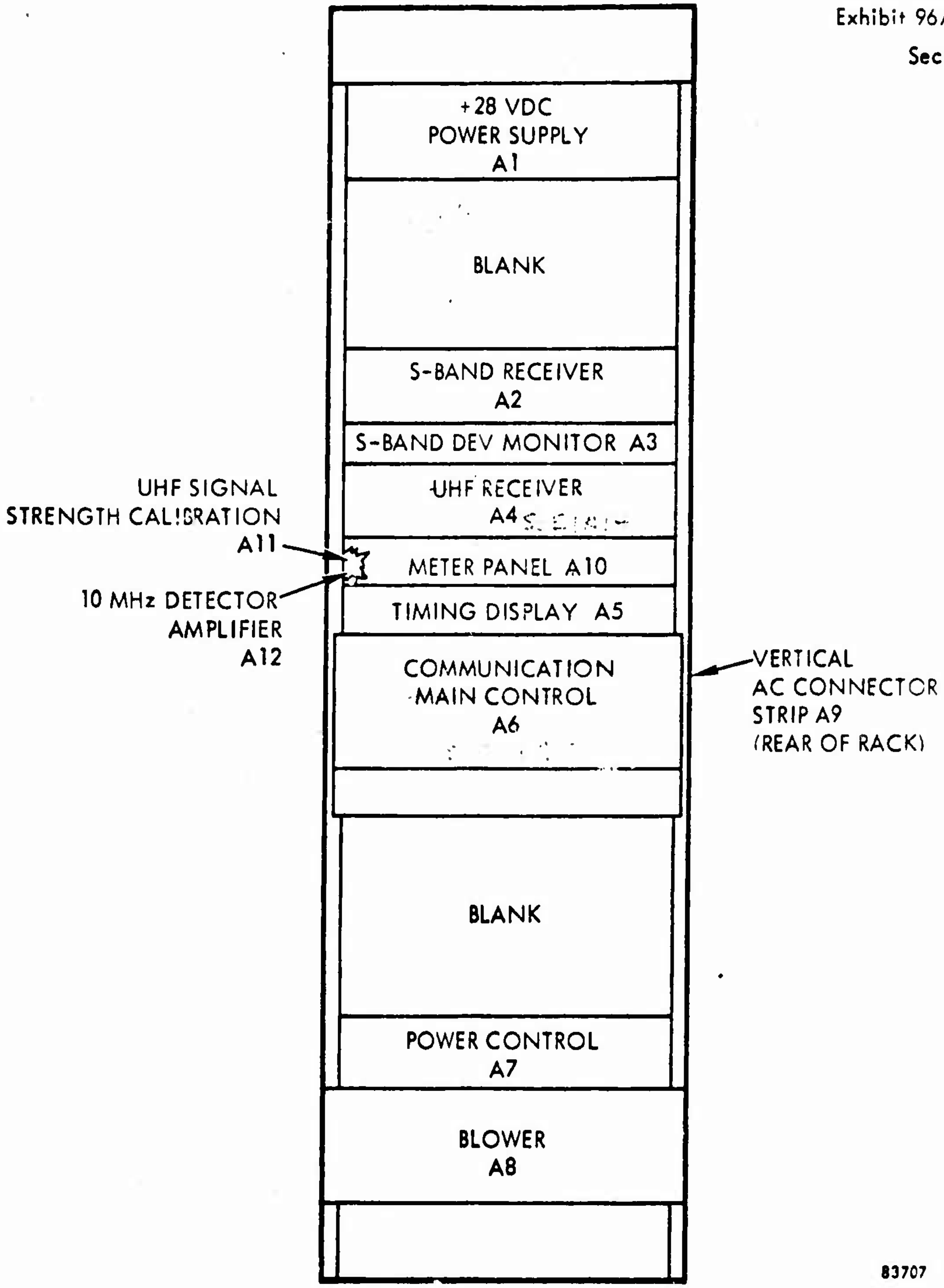
Model (Part No.)	Noun	Quantity
485	Osciloscope	1
7702B	Recorder	1
8801A	Pre amp	2
1062A	Recorder cart	1

FIG 6 (Con't)



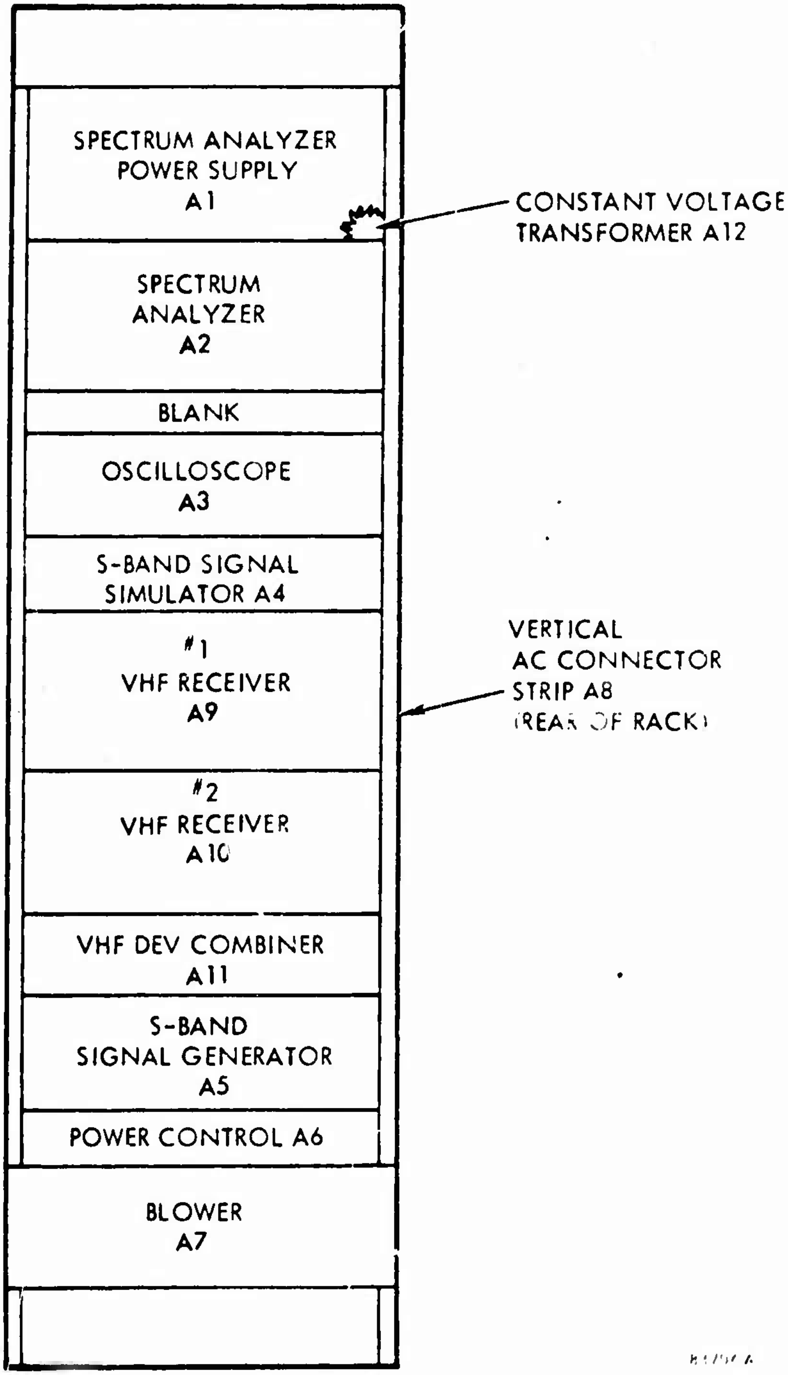
(U) Receiver Calibration Cabinet (1A1), Front View

FIGURE 7 FAIR. CRS RACK ELEVATIONS



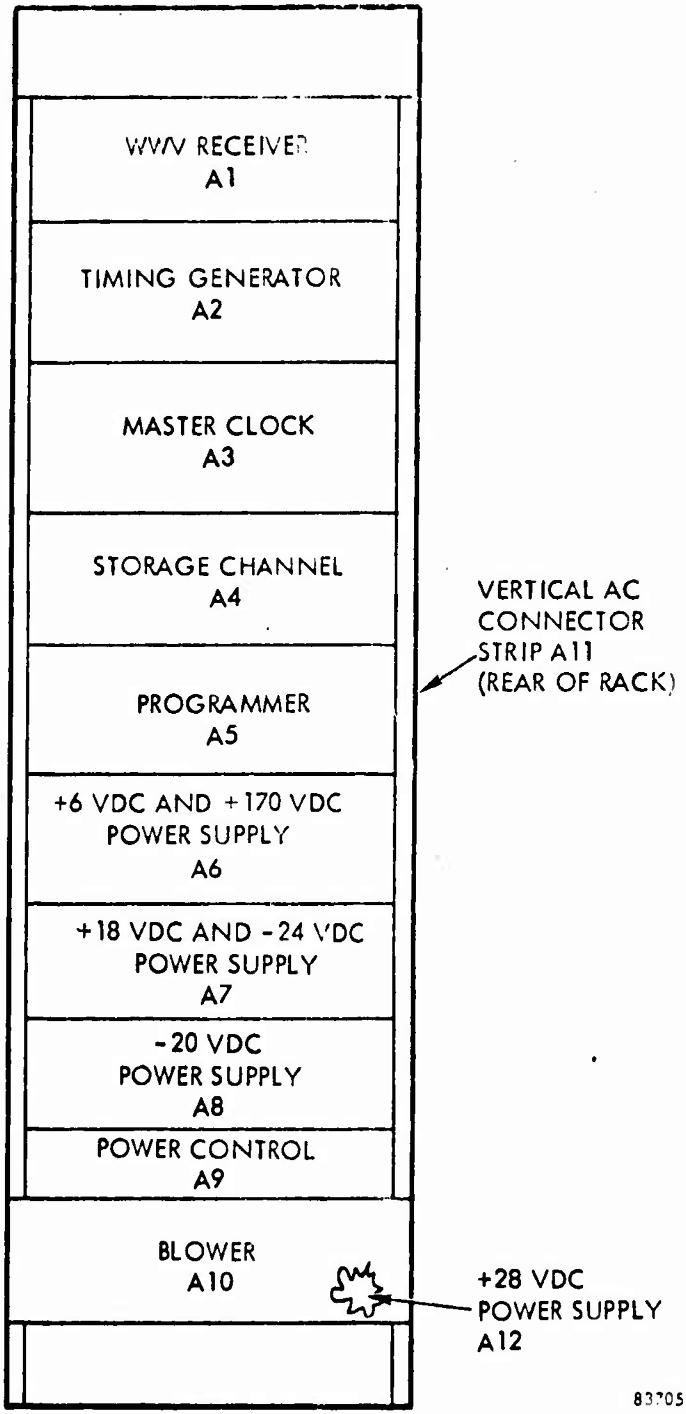
(U) Receiver/Transmitter Control Cabinet (1A2), Front View

FIG 7 (Con't)



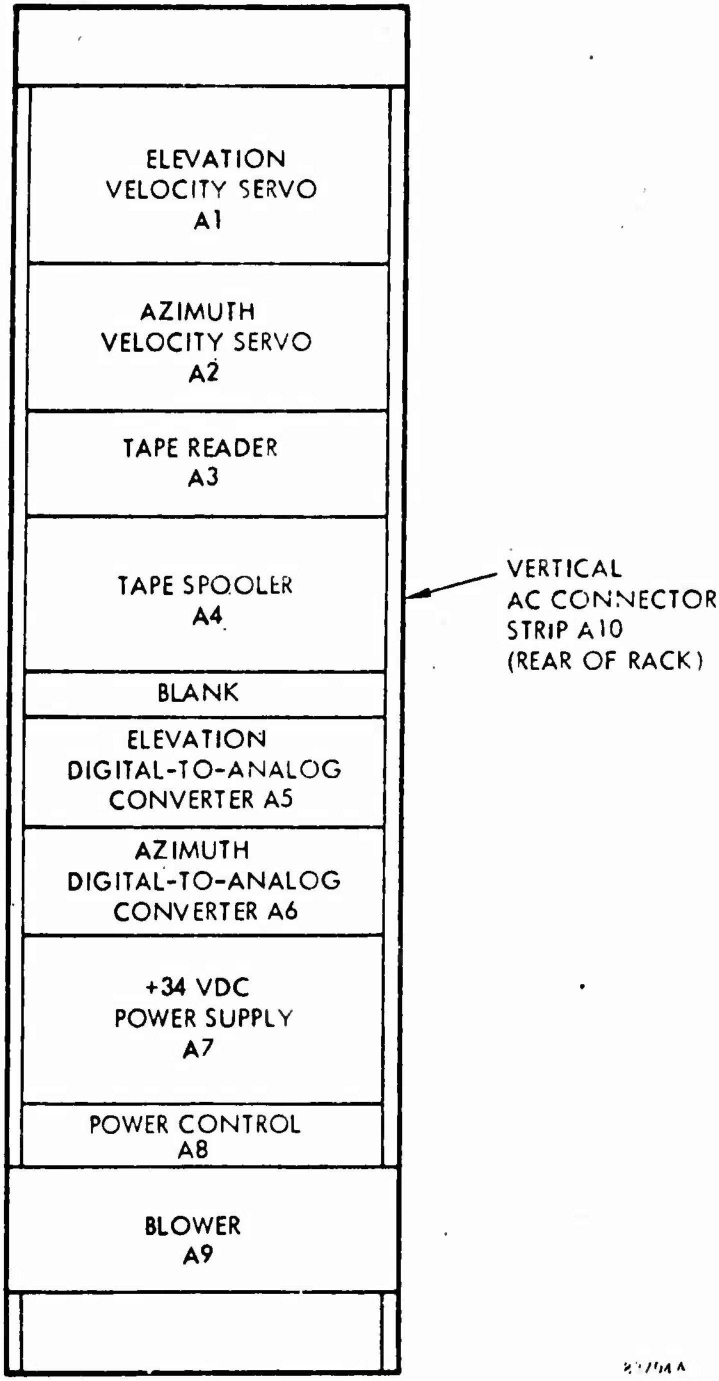
(U) Receiver Simulator Cabinet (1A3), Front View

FIG 7 (Con't)



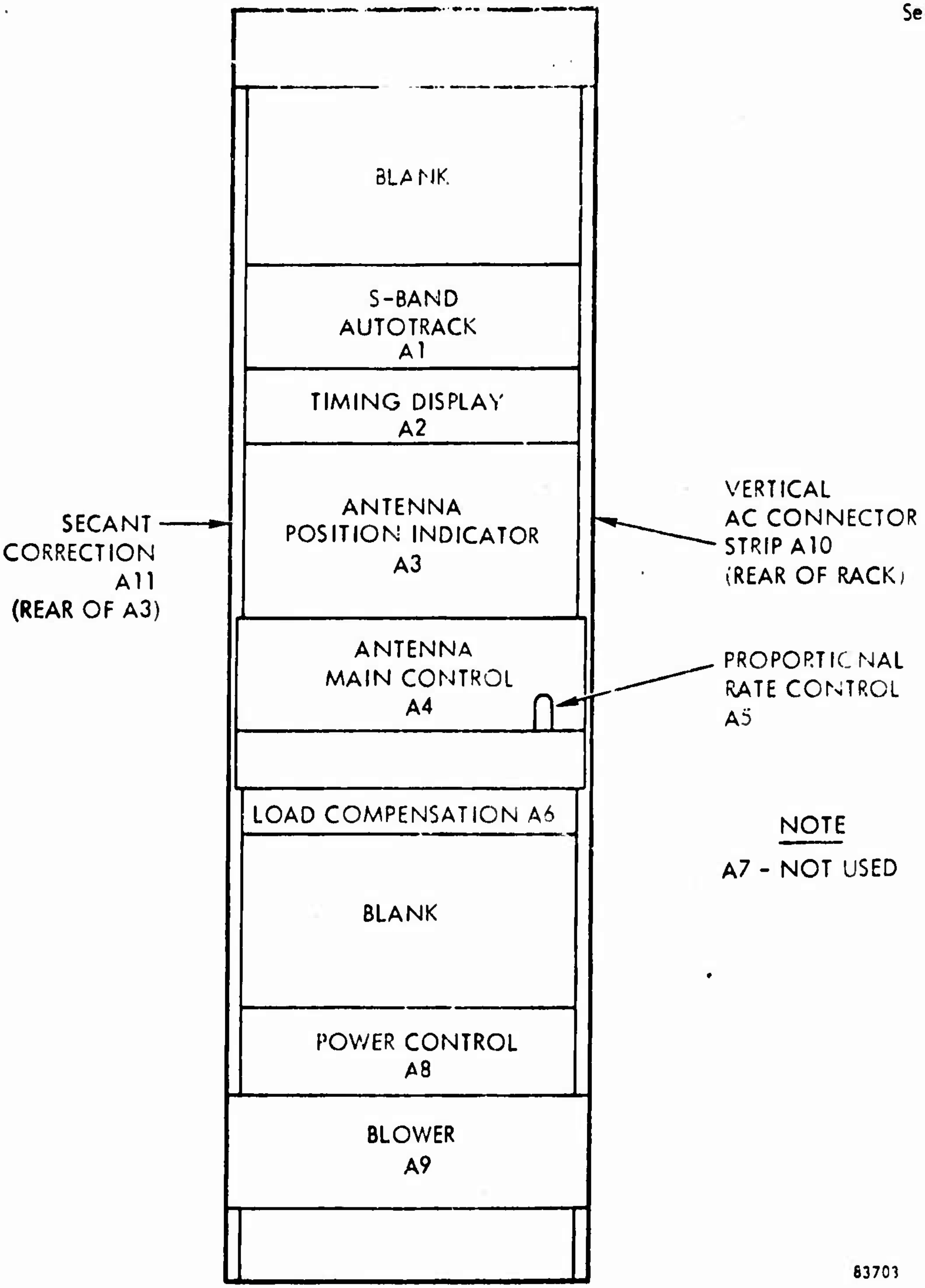
(U) Timing Cabinets (1A4), Front View

FIG 7 (Con't)



(U) Antenna Programmer Cabinet (1A5), Front View

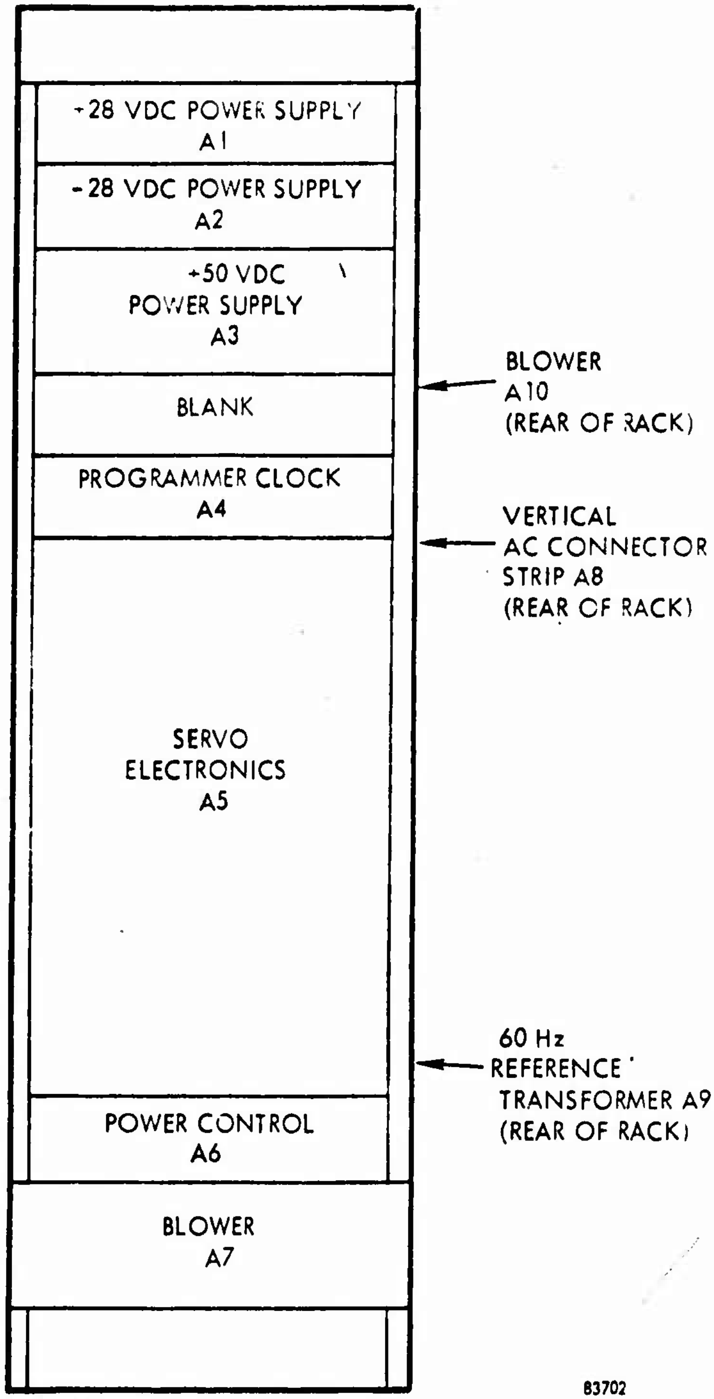
FIG 7 (Con't)



(U) Antenna Control Cabinet (1A6), Front View

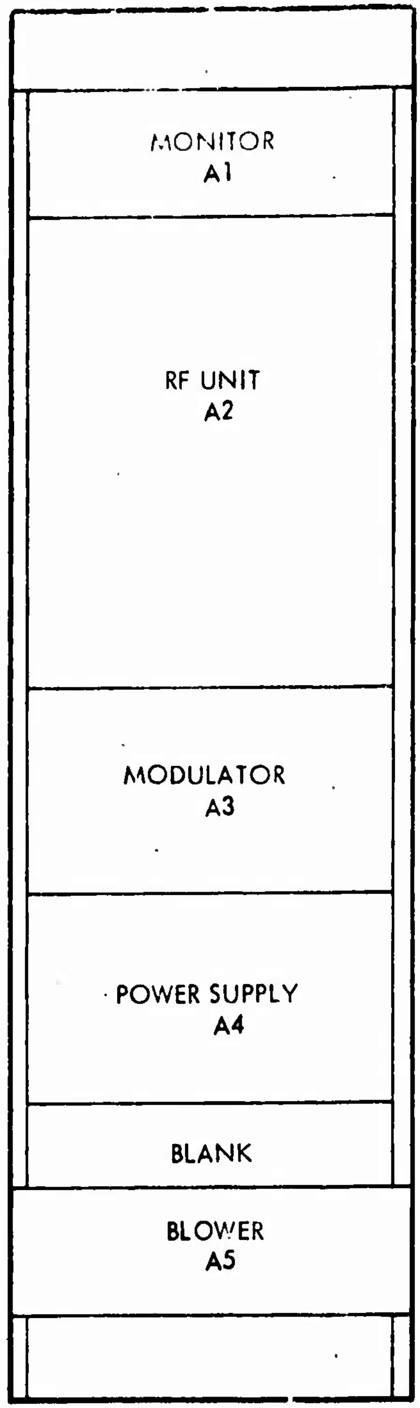
FIG 7 (Cont)

UNCLASSIFIED



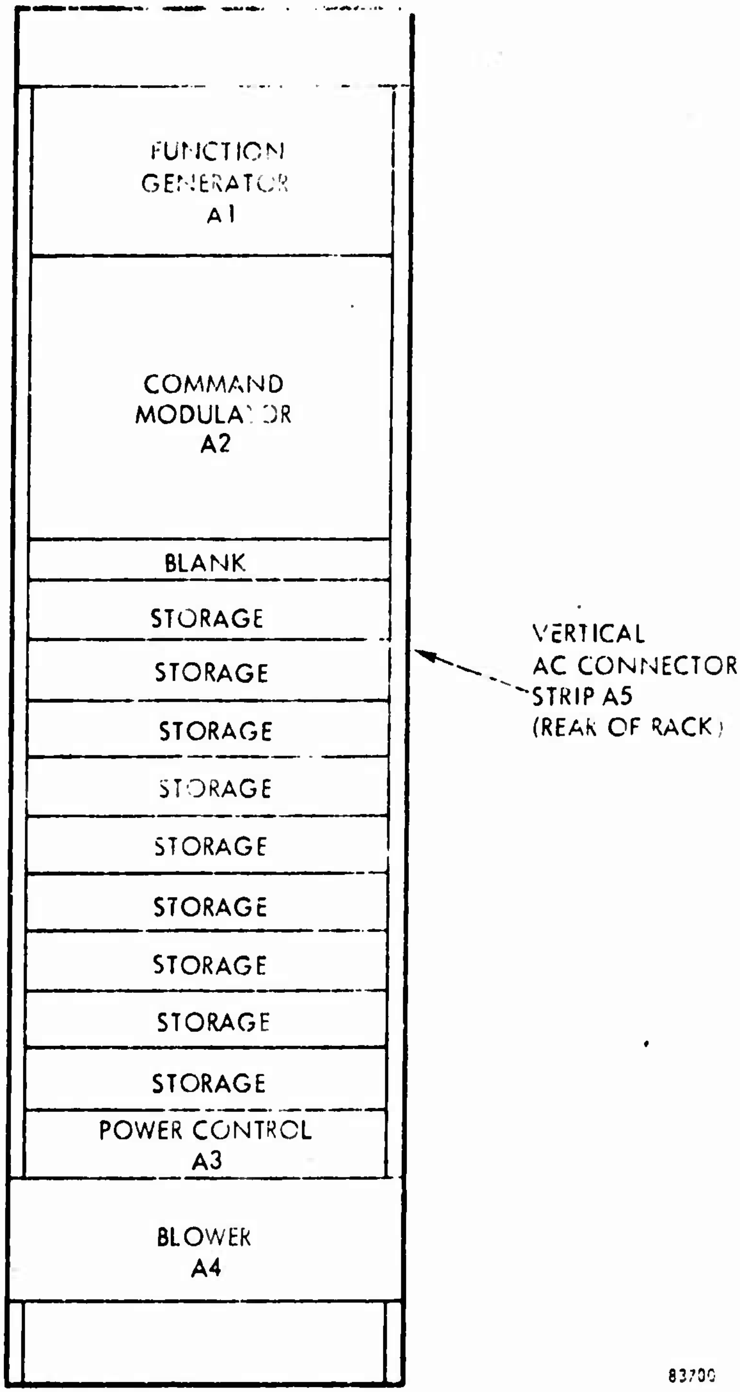
(U) Servo Cabinet (1A7), Front View

FIG 7 (Con't)



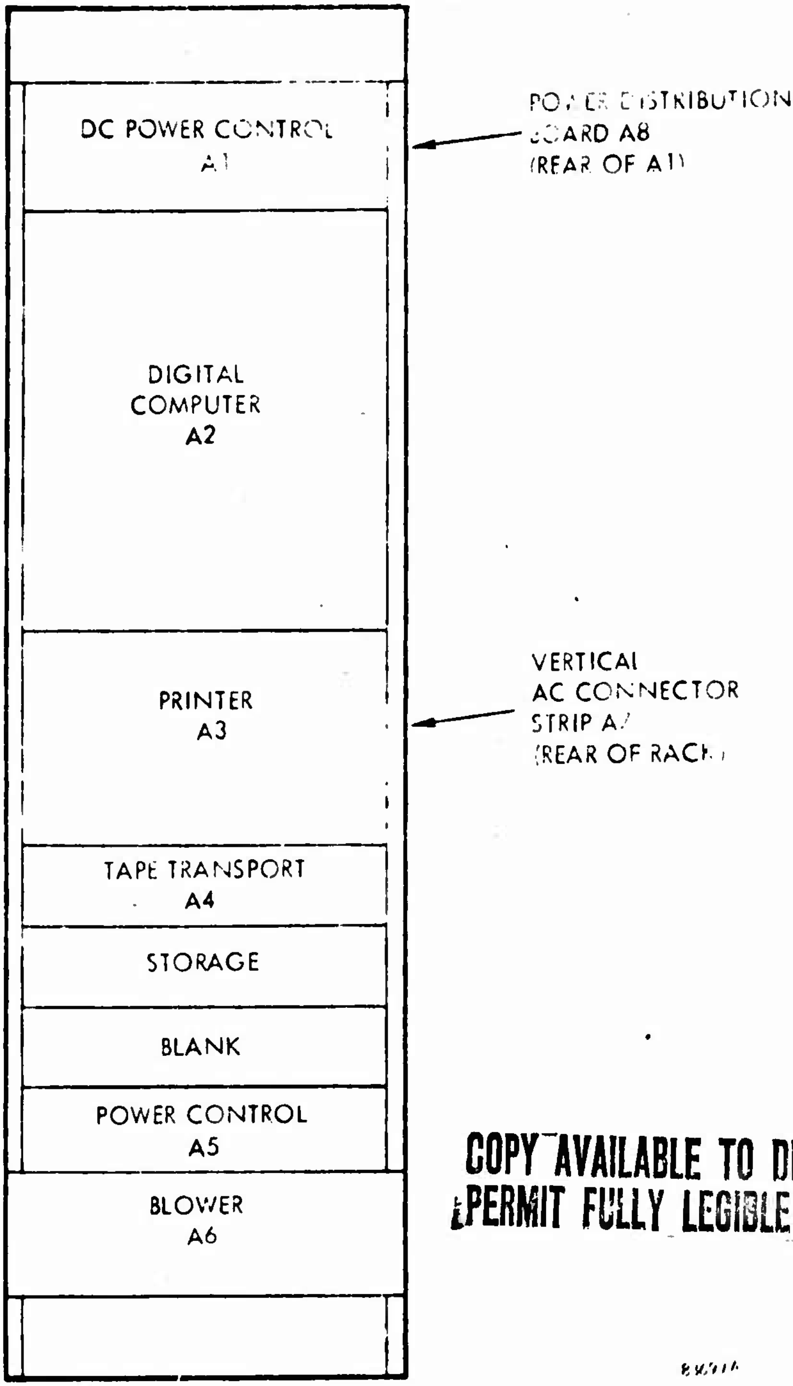
(U) Transmitter Cabinet (1A8), Front View

FIG 7 (Con't)



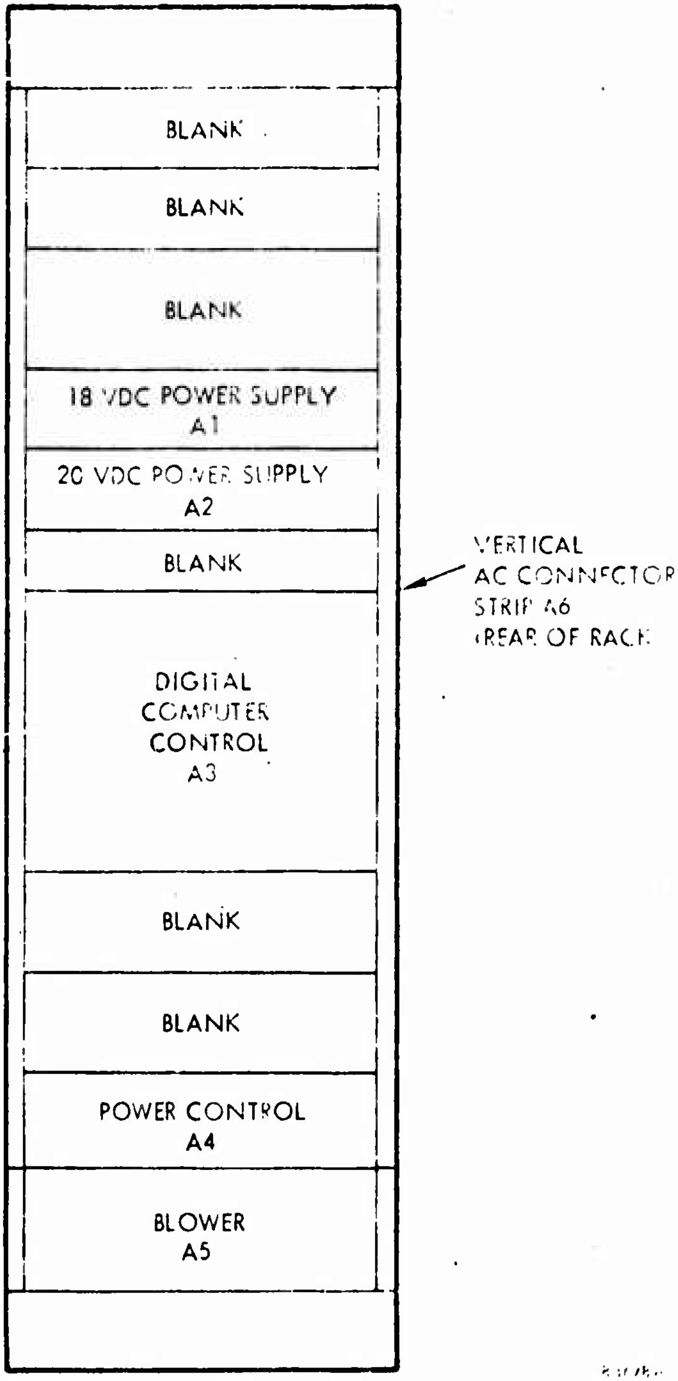
(U) RF Exciter Cabinet (1A9), Front View

FIG 7 (con't)



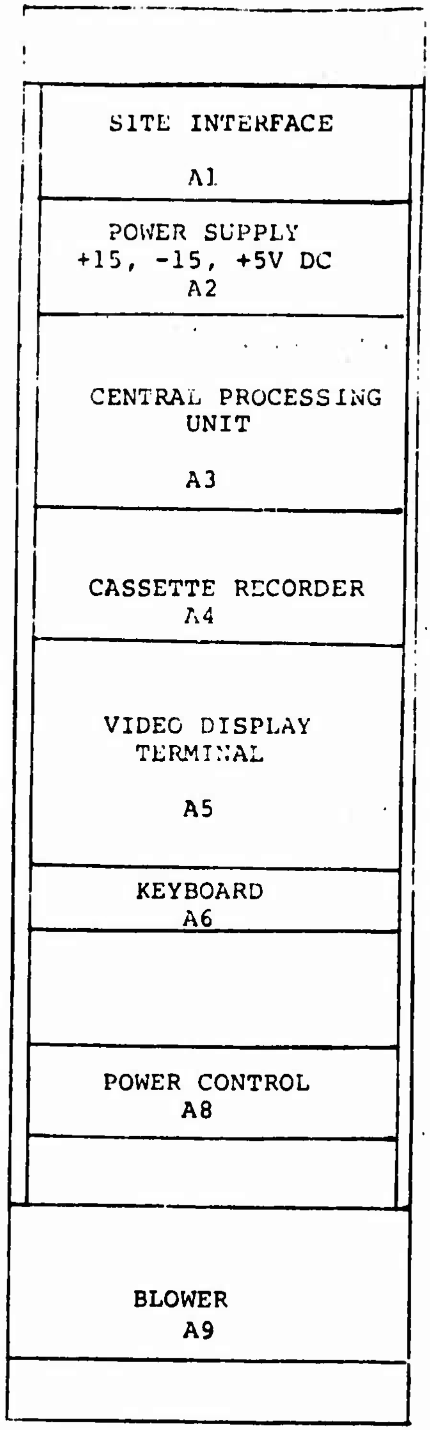
(U) Command Control Electronics Cabinet (1A10), Front View

FIG 7 (Con't)



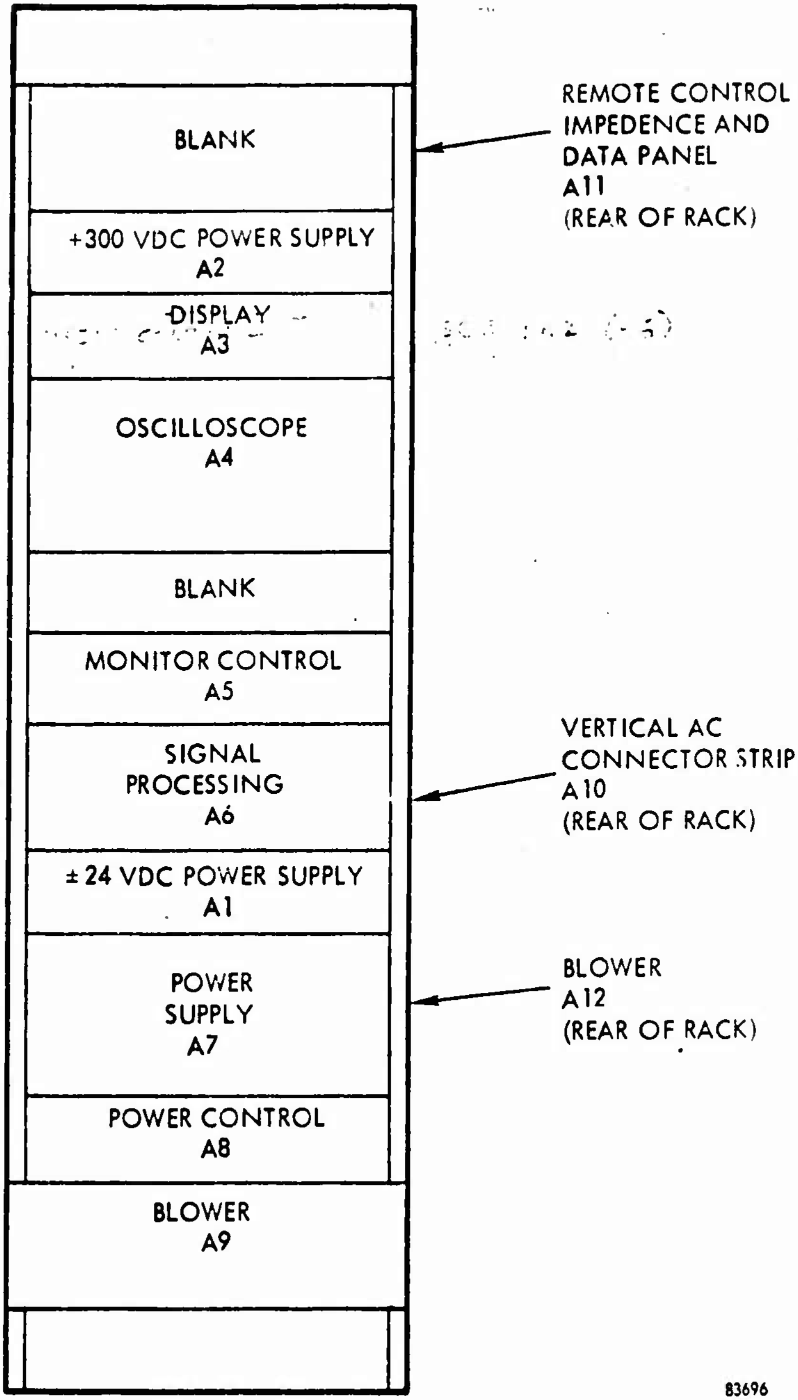
(U) Command Control Cabinet (1A11), Front View

FIG 7 (Con't)



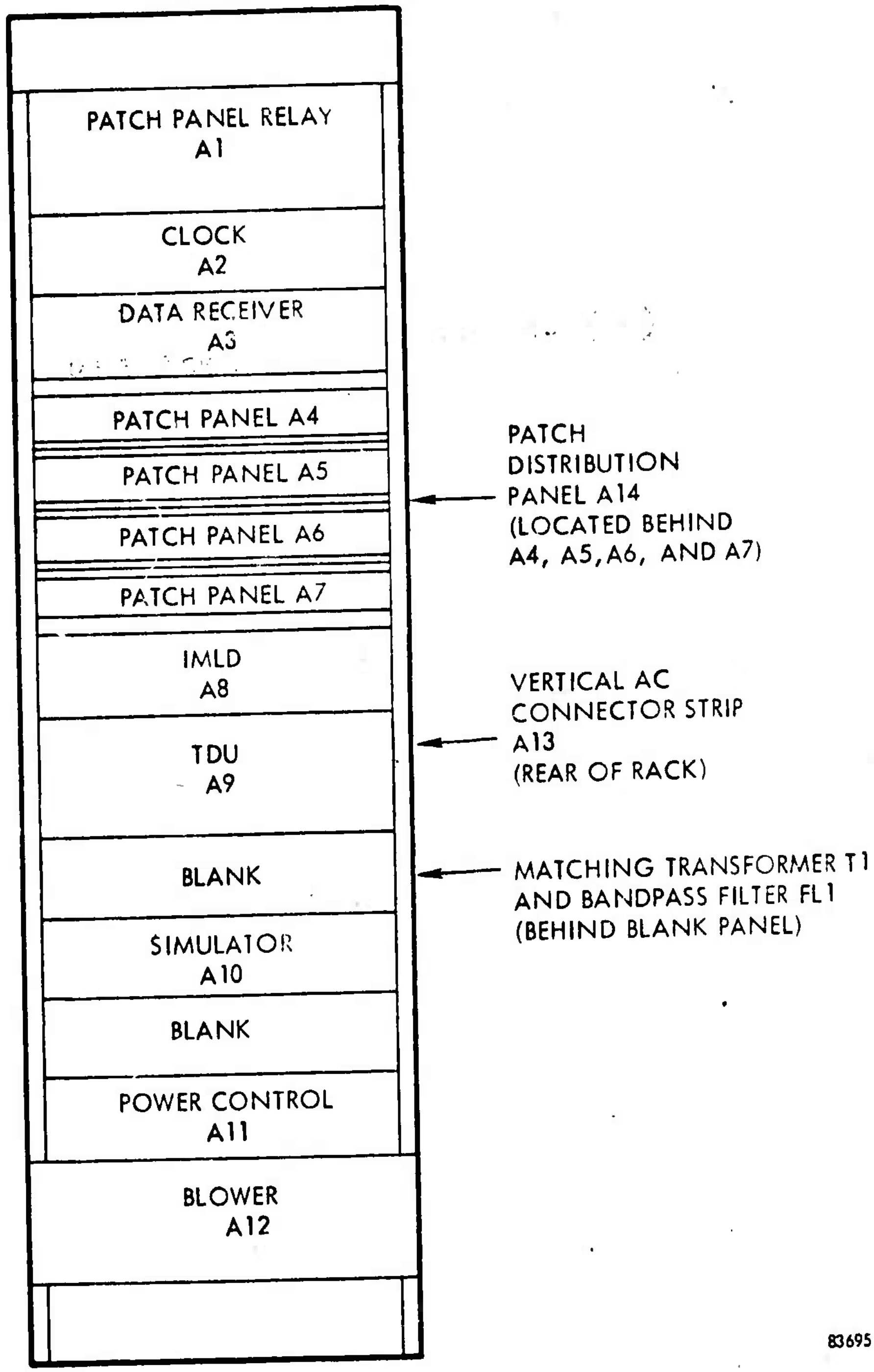
INTEGRATED COMMANDING SYSTEM (1A12),
FRONT VIEW

FIG 7 (Con't)



(U) Data Display Cabinet (1A13), Front View

FIG 7 (Con't)



(U) Patch Panel Cabinet (1A14), Front View

FIG 7 (Con't)

(TYPED FROM ORIGINAL)

YDO (Capt Shrum/32328)

Block 5D Support Requirements Update

AFBCF (DVSP/Capt Lauck)

1. This letter outlines what we envision to be the SCF requirements for orbital and launch support of the Block 5D spacecraft (late 1974). This letter is not intended to be, nor should it be construed to be a formal requirements document. This information should be used only for preliminary planning purposes.

2. Firm Requirements

a. Tracking, receiving, recording and microwave relaying simultaneous wideband data readouts at 1.024 megabit per second (mbs), 1.3312 mbs or 2.6624 mbs on two different S-band frequencies. Any combination of two of the three rates on the two frequencies is possible, including the same rate on both frequencies, except 1.024 mbs rate on both frequencies. The two S-band frequencies are 2207.5 MHz and 2267.5 MHz. The modulation type is phase modulation by bi-phase NRZ-L data. The data may be encrypted. The expected readout time is 15 minutes. A less likely mode is a readout on a single frequency at any one of the three data rates. Tracking of these two frequencies is required, but tracking would most likely be accomplished on the Equipment Status Telemetry (EST) frequency (see 2C below). This requirement is for orbital support only at VTS.

b. Tracking, rec[illegible]ng, recording, and microwave relaying wideband data at 1.024 (mbs) on a frequency of 2252.2 MHz. The modulation type is phase modulation by bi-phase NRZ-L data. This requirement is over and above that outlined in paragraph 2a.

c. Tracking, receiving, recording, and microwave relaying a narrow band EST readout at approximately 60 kbs on ascent, 10 kbs or 2 kbs on orbit on 2237.5 MHz. The modulation type is phase modulation by bi-phase NRZ-L data. The expec[illegible]ed readout time is from L/O to LOS on ascent and rise to fade

FIGURE 8 VTS SUPPORT FOR BLOCK 5D

on orbit. This requirement is for ascent and orbital support at VTS and rev 0.9 support at INDI.

d. Tracking, receiving, recording and microwave relaying a wideband data readout at any one of the three data rates discussed in 2a on the link discussed in 2c. This would be likely only in the event of a failure of one of the two primary data links discussed in 2a.

e. Tracking, receiving, recording and microwave relaying a wideband data readout at 1.024 mbs on 2207.5 MHz, 2252.5 MHz and 2267.5 MHz. The expected readout time is 15 minutes. This requirement is for orbital support at HTS. The HTS will need to handle only one frequency at any given time.

f. Microwave relaying any combination of the digital signals discussed in 2a, 2b, 2c and 2d from VTS to a fixed location on VAFB. (The microwave equipment would be provided by the Program Office.)

g. Pre-launch nominal ephemeris predictions and early orbit tracking support requirements will probably not be significantly different from the present. Because of the increased ephemeris requirements of the Block 5D spacecraft, a greater vehicle location accuracy may be required before termination of SCF ephemeris support.

3. No Requirement Envisioned

a. Commanding the spacecraft. The uplink frequency of 1835.791 MHz, however, is SGLS compatible.

b. Decommutating and/or data processing of mission and telemetry data.

4. Time Frame

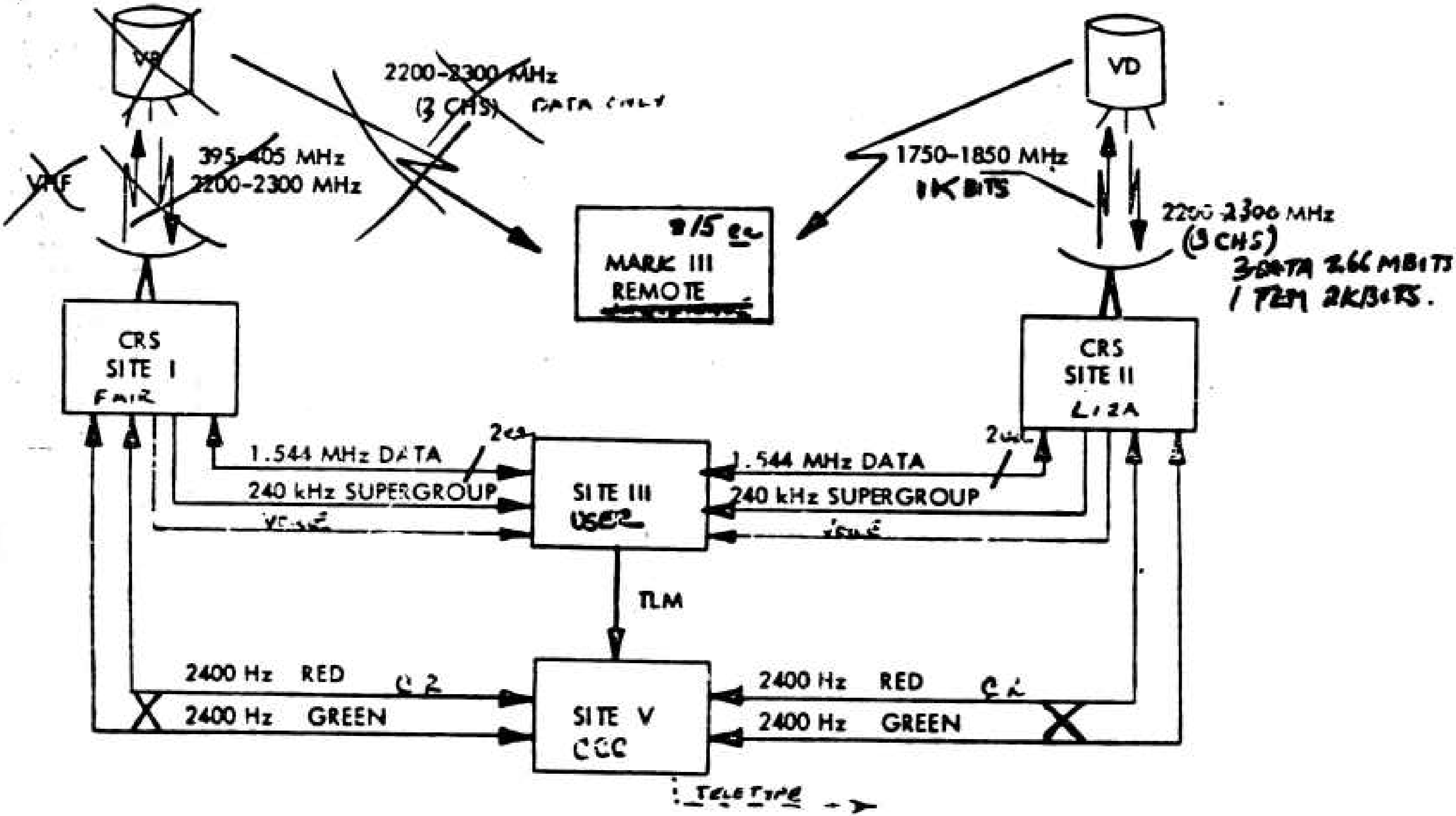
a. The microwave relay link should be complete by 1 July 1974.

b. The remaining requirements should be complete by 31 Dec 1974.

5. Request your response to these projected requirements by 19 Oct 1973. Of particular interest is how these support requirements mesh with your existing projections in capability for the 1974-1975 time period.

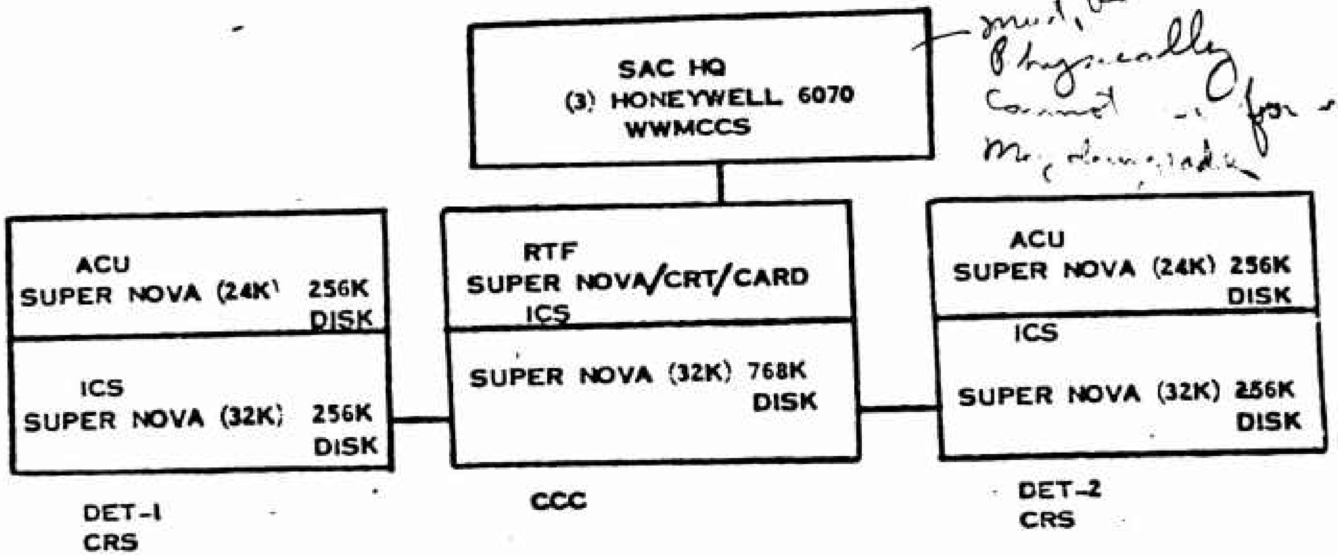
GEORGE L. WATTS, Major, USAF
Director of Operations
Defense Systems Application Program Office

FIGURE 8 (Con't)



OVERALL SYSTEM BLOCK DIAGRAM

FIGURE 9 BLOCK 5D SYSTEM BLOCK DIAGRAM



COMPUTER SYSTEM

- INTEGRATED COMMAND SYSTEM (ICS)
- REMOTE TERMINAL FACILITY (RTF)
- ANTENNA CONTROL UNIT (ACU)
- WORLD WIDE MILITARY COMMAND & CONTROL SYSTEM (WWMCCS)

FIGURE 9 (Con't)

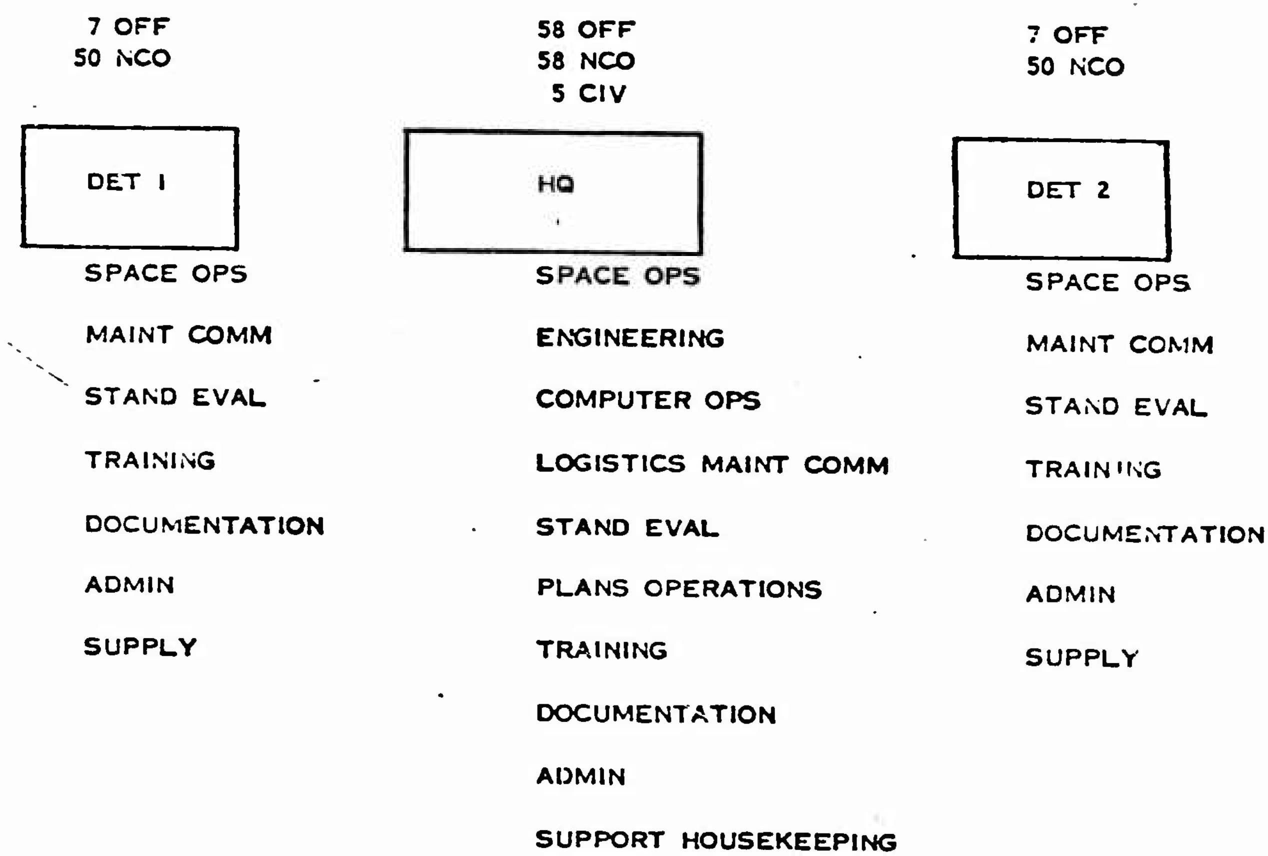


FIGURE 9 (Con't)

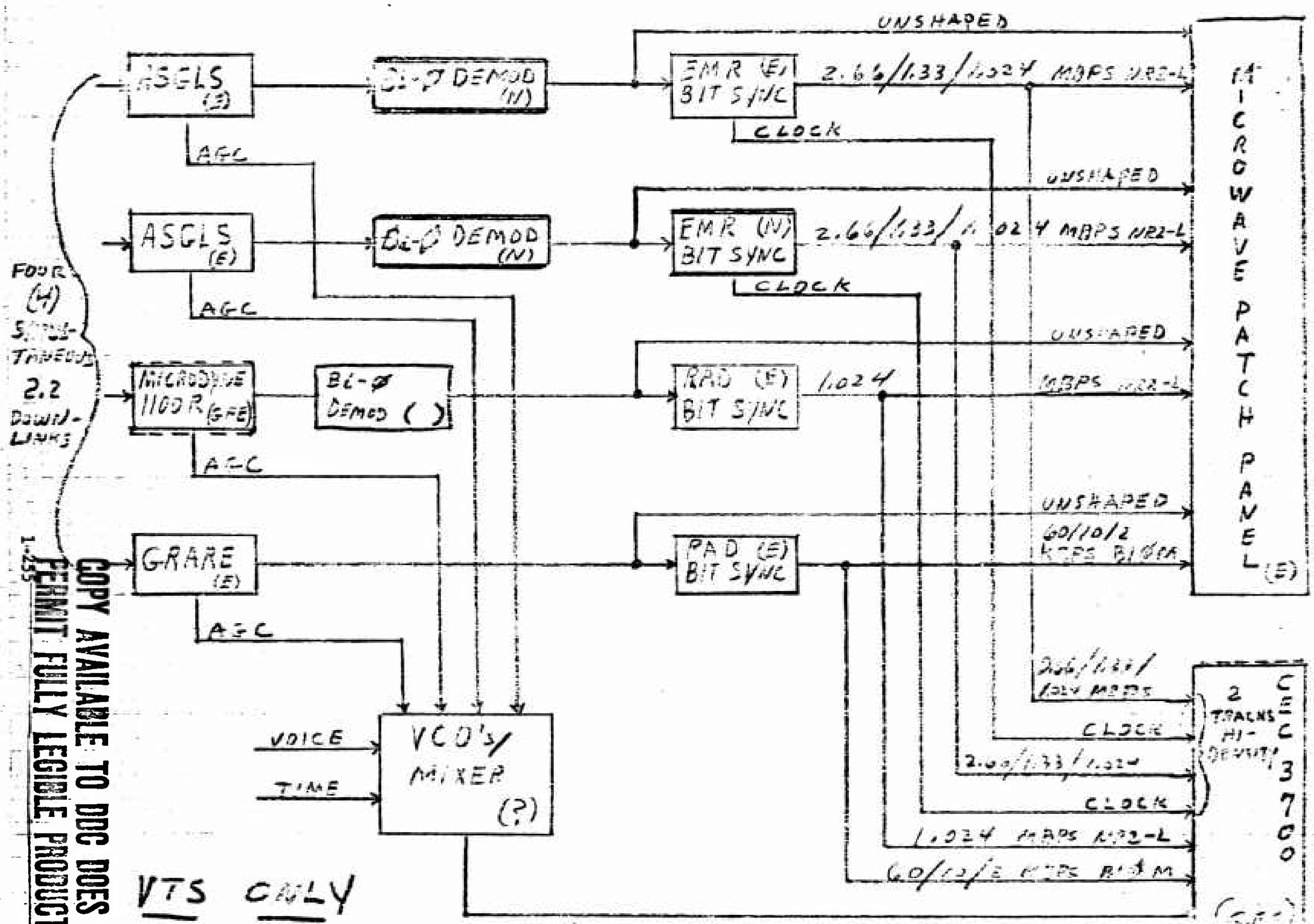


FIGURE 10 VTS SUPPORT FOR BLOCK 5D

6.3 NWL

The following data referes to existing NWL facilities.

PHILCO Ford

Intra Company

27 November 1973

TO: John Theibault

FROM: D. E. Ekman

SUBJECT: Trip to Naval Weapons Lab

During the afternoon of 16 November 1973, C. G. Hilton and I met with Dr. Robert Hill and others at the Naval Weapons Lab in Dahlgren, Va. to discuss their orbit determination program CELESTE and its possible application to DNS. CELESTE is a new program and replaces ASTRO, which was developed about 1960 and is very similar to TRACE. CELESTE represents a significant departure from the ASTRO/TRACE structure in that considerable use is made of linear theory so that integration is performed only once for a given set of data.

CELESTE treats only doppler measurements, which are treated as range differences. Ionospheric refraction effects are removed at the tracking stations by use of two frequencies. Tropospheric refraction is modeled within CELESTE, using a model developed by H. Hopfield of Johns Hopkins. The data from each station pass are edited to remove outliers (a feature lacking in TRACE) and the normal equations are formed and stored. By storing pass normal equations rather than raw data, subsequent processing is reduced to matrix manipulations without the need for repeated integration. A typical pass matrix (set of normal equations) consists of six orbit elements, one drag parameter, three thrust parameters, a radiation pressure multiplier, three station coordinates, and three bias terms (frequency, frequency drift rate, and tropospheric refraction.) During processing, pole position data can be developed from station location parameters Note that CELESTE does not solve for geopotential coefficients. The geopotential model used is complete to 19th order, with selected coefficients up to 27th order, for a total of 480 terms. This model is available as WGS73 (classified Confidential) and was developed using data from as many different inclination orbits as were available over the past ten years. The program that solves for these coefficients is GEO, which was developed along with ASTRO and is soon to be replaced by TERRA, a new program developed along with CELESTE.

When used with TRANSIT spacecraft, fits are made with 48-hour data spans. Residuals are about 1 to 1.5 meters. Prediction accuracy is claimed to be about 50 meters for 48 hours, and 70 meters for 72 hours. Accuracy checks have been performed using laser data from GEOS satellites, geodimeter survey data, and polar wander data compared with independent determinations. These checks appear to support a claim of determination accuracy to a few (less than 5) meters.

Integration is performed by a 10th - order Gauss-Jackson formulation (Cowell form). Since circular orbits are being determined, step size is held fixed during integration. To yield two-week closure accuracy of one meter, 100 mile orbits require a 30 second step size; 500 mile orbits permit a 1 minute step, and Dr. Hill estimates that 11000 mile orbits will permit a 15 minute step.

CELESTE presently runs at NWL on a CDC 6700, all in single-precision FORTRAN IV except for a CDC matrix manipulation package which presumably is written in assembly language, and except for the refraction model which uses some double precision. CELESTE also operates on a Univac 1108, an IBM 7090, and an SEL 86.

For DNS application, NWL recommends using 30 days of data for a fit, and integrating for another 90 days. As real time progresses slide the 30-day interval forward and improve the prediction by linear theory without re-integrating. This is much like the piggyback scheme, but the periods seem very large. NWL have not done any simulation to verify the ability to predict and update for these long intervals while maintaining accuracy.

D E Ekman

D. E. Ekman
Space Systems Technology Department

DEE:ev

cc: J. Brown
D. Potter

PHILCO Ford

Intra Company

23 November 1973

To: L. G. Walters

FROM: C. G. Hilton

SUBJECT: Trip to NWL, Dahlgren, Va.

1. General

On 16 November Don Ekman and I met with Dr. Robert Hill and other NWL personnel to discuss the characteristics of Celeste, their new orbit determination program. Celeste has replaced Astro, which was developed about 1960.

Neither Astro nor Celeste solves for any geopotential coefficients. That is done by Geo, which will be replaced soon by Terra, a new program which NWL has formulated.

Celeste uses time (UTC) only as an independent variable. The coordinate axes are either Mean Equator and Equinox of 1950.0 or True Equator and Equinox of Epoch. Epoch is usually taken at the beginning of a two-day fit on Transit satellites.

2. Data Handling

Station coordinates are computed with respect to these axes. There are corrections however for the position of the instantaneous pole and for the earth rotation rate. The polar coordinates and rotation rate are possible solution parameters.

The data processed are doppler measurements, which are treated as range differences. Two frequencies are used so that the stations can remove the effects of ionosphere refraction. (Only the fixed stations have this capability, the geoceivers do not.) Tropospheric refraction is removed by using the model developed by Helen Hopfield of APL.

3. Orbit Improvement

The data from each station pass are edited and the normal equations are formed. The state vector consists of the six orbit parameters (M-N elements), a "canonical" drag parameter, three orbit adjust components, a radiation pressure multiplier, three station coordinates and three biases (satellite oscillator frequency, drift rate and tropospheric refraction.) The pole position partials can be formed from the station coordinate partials. The A^TA and A^TB are then stored away for future processing.

The partial derivatives with respect to the orbit elements and physical model parameters are integrated along with the orbit. Even though the differential correction can be iterated, the A^TA and A^TB are never recomputed. TRANSIT corrections converge in one iteration, but lower orbits require several iterations. Note that the ephemeris is computed only once. Corrections to the elements are taken out of the residuals by use of the partial derivatives. Constraints on the solution can be imposed by adding values to the diagonal of A^TA.

Celeste does not have a multisatellite capability although multisatellite solutions have been performed "Off-line" by extracting the relevant matrix quantities.

4. Force Model

Celeste uses an exponential model of the atmosphere at TRANSIT altitudes. The "canonical" drag parameter means that the partials are formed with respect to a unit ballistic coefficients so that the orbit determination interval (ODI) can be divided into 5-6 spans during each of which a separate drag multiplier can be solved. This is used more at lower altitudes than for TRANSIT orbits.

Lunar and solar gravitational attractions are then computed but no other planets are used. NWL has generated its own lunar and solar ephemerides. The sun is tabulated at 24 hour intervals, the moon at 12 hours. The same solar ephemeris is used to compute radiation pressure. A single multiplier is used for radiation pressure but NWL is experimenting with a method of representing illuminated area (weighted by albedo) from photography of the satellite before launch.

The latest earth model is NWL 10c, which has 480 terms, with harmonic terms up to 27th order. It has been adapted as WGS73. The Geo determination used satellites in orbits at 12 different inclinations. This is the same model which was presented recently at SAMSO (J. L. Arsenault attended). The coefficients are classified confidential.

The effect on the geopotential of the solar and lunar tides are also computed. The same ephemerides are used for this perturbation.

5. Integration and Error Estimates

The numerical integration is performed by a 10th order Gauss-Jackson formulation. The starting tables are formed laboriously as Cowell did it 80 years ago. (Dr. Herget still visits NWL occasionally.) Constant step-sizes are used since all orbits are nearly circular.

The following step-sizes are used to achieve closure better than one meter over two weeks of integration:

Orbit Altitude (n.m.)	Step-Size (mins)
100	0.5
500	1.0
1100	15.0

Internal accuracy of a two-day fit to a TRANSIT satellite is within a few meters. User accuracy is claimed to be better than 50 meters after a two-day prediction and better than 70 meters after a three-day prediction (i.e., the error increases about a meter per hour). Of course, there is a threshold; at 16 hours the prediction error is between 20 and 30 meters.

6. DNS Application

The following usage of Celeste for DNS was given to us as well as to the General Dynamics personnel who visited on the previous Wednesday:

Fit 30 days of data, obtained in 15-minute passes and integrate another 90 days (with variational equations). Use a sliding 30-day ODI to obtain improvements to the ephemeris over the next two or three days. We responded that we had a similar scheme but had throught of only 7-day ephemerides.

7. Program Availability

Celeste runs on a CDC 6700 at NWL. Only single precision is needed except in the refraction model, which uses some double precision. The version at DMA runs on an 1108 and uses double precision. Celeste has also been run by SPASUR on a 7090. Dick Farrar at Aerospace has the Orbit Determination Overlay. Aerospace works from ephemerides furnished by NWL.

There are other overlays for Data Preparation, Data Editing and Orbit Integration. The largest overlay uses 125K (octal) words. The program is in FORTRAN IV. All subroutines except the CDC Matrix Routines were written by NWL.

Documentation is in draft form, partly manuscript, partly typed. Capt. Birnbaum directed that no documentation be given to us (or GD). Publication is 5-6 months off. We looked at the documentation. It is in fairly free form which looks nothing like a Part I Spec.

CHilton
C. G. Hilton

cc: D. R. Potter (for DNSS distribution)
J. D. Enright
C. G. Hilton

PHILCO Ford

Intra Company

28 September 1973

DNSDP-JTW-074

To: G. R. Hickcox

From: J. T. Witherspoon

Subject: Trip Report, Naval Weapons Laboratory, September 27, 1973

J. E. Theibault and the undersigned visited the Naval Weapons Laboratory, Dahlgren, Virginia 22448 on September 27, to meet with Dr. R. W. Hill (707-663-8046) and Mr. R. J. Anderle (707-663-8159). The principle purpose of this visit was to obtain information on the methods and techniques used for data collection, data processing and orbit determination for the Navy Navigation Satellite System (NNSS). Plans to visit Roger L. Easton, Timation Program Manager (202-767-3084) and C. A. Bartholomew (202-767-2595), Naval Research Laboratory, Washington, D.C. 20375, were unsuccessful due to schedule conflicts.

Dr. Hill and Mr. Anderle have been involved in satellite orbit determination and geodetic position determination using satellite observations for over 12 years. They represent the focal point for all Navy supported navigational system data processing. Their current activities are summarized below in terms of three current applications:

1. Geodetic Tracking Network
2. Transit Operational Network
3. Timation Satellite Program

Geodetic Tracking Network

NWL is responsible for satellite orbit determination and geodetic position determination for the Geodetic Tracking Network.[1] This network consists of 15 to 20 stations distributed around the world which track 5 transit satellites in near circular polar orbit at altitudes of about 1000 km. Vehicle ephemerides are based on a least square fit of doppler tracking data observed over a 48 hour interval. The doppler tracking data is derived

[1] Geodetic Control with Doppler, R.J. Anderle, American Society of Photogrometry, March 1973.

from two coherent received signals at 150 MHz and 400 MHz. Measurements are made discontinuous each 4 seconds over intervals of less than 1 second, or made continuously at 10 to 20 second intervals. Data at the two frequencies are combined to correct for first order ionospheric refraction. The measurements are punched on teletype tape and transmitted to the Applied Physics Laboratory of Johns Hopkins University where the data are transferred to magnetic tape and sent to the Naval Weapons Laboratory once each day. Observations are first calibrated and filtered. Time signals transmitted by the satellite are used to correct local station clocks. An average time correction is determined for each pass. Satellite position is computed by numerical integration of the equations of motion of the satellite which include effects of atmospheric drag, solar radiation, lunar-solar gravitation, lunar-solar solid earth tides, and earth gravity. The earth gravity is defined by a spherical harmonic expansion which includes about 450 terms. Tracking data obtained over the 48 hour interval is processed to estimate the following parameters:

- Six orbital elements
- One atmospheric drag coefficient
- One satellite frequency bias for each pass (approximately 200 passes per batch)
- One tropospheric refraction bias parameter
- Two earth axis coordinates

These computations are performed on the NWL CDC 6700 computer in a batch processing mode. The cost of each batch is between $200 and $400 and requires several hours of time on the machine. NWL estimates the accuracy of the resulting orbit determination at 2 meters. The results of the NWL process are distributed to various agencies for post-pass analysis. Prediction accuracies for intervals of 12, 24, 48, and 72 hours after a two-day orbit fit are estimated at 8, 15, 35, and 70 meters respectively.[2] Further description of the geodetic tracking network can be found in reference 1.

Transit Operational Network

The responsibility for operational control of the five transit satellites is assigned to the Navy Astronautics Group at Pt. Mugu, Capt. Liebert, Commander. This group operates four operational tracking sites at Maine, Minnesota, California and Hawaii, and a data computation facility at Pt. Mugu. This network provides real time ephemeris determination, satellite commanding control in support of various operational real time users. Tracking data is collected from the operational sites and transmitted directly to Pt. Mugu. The data is similar to that used by the geodetic tracking sites but with some differences due to different receiving

[2] Accuracy of a Predicted Satellite Position, L.K. Beuglas, M.S.Douglas, NWL TR2758, June 1972

equipment. Observations from each satellite are collected over a 12 hour period. This data is combined with 24 hours of old data for orbit determination using a conventional least square process. This process produces a new estimate of satellite orbital parameters each 12 hours plus correction terms for prediction of satellite position at two minute intervals for 16 hours past the end of the tracking data interval. These data are then loaded into the satellite and are broadcast every two minutes to potential users. The Pt. Mugu facility uses a 7094 computer, requires approximately 4 hours to process each new data batch and to reload the satellites. The program used is one developed at APL a number of years ago and is based on earlier programs at NWL. The operational network orbit determination is good to 20 meters over the 12 hour tracking interval, an average of 40 meters over the 16 hour prediction interval, with a maximum error of 80 meters at the end of the prediction interval. These satellite predictions are independent of each other. Neither NWL or Pt. Mugu have multi-satellite orbit determination programs at this time.

Timation Three

NWL is in the process of developing an extension of their existing computer programs called CELESTE. This program will be designed to support future Navy programs currently planned such as Timation Three. The use of side tone ranging (STR) and the medium altitude orbit for Timation Three will require estimation of a different set of system parameters. At this time the following parameters are planned:

1. Six orbital elements per satellite
2. One solar pressure parameter (CPAW) per satellite
3. Two vehicle clock parameters (time bias and drift rate)
4. Two clock parameters for each station
5. Two pole position coordinates
6. An undetermined number of harmonic geopotential coefficients

Current plans do not include a multi-vehicle solution. However, NWL people agree that a multi-vehicle orbit determination would be required to get DNSDP accuracy objectives in real time.

Geopotential Modeling

Much of NWL's work over the past years has been focused on refinement of the geopotential model used in their orbital determination programs. The current model used is based on a 25 by 25 coefficient matrix which has been truncated to approximately 450 terms by neglecting insignificant terms.[3]

[3]"Effect of Neglected Gravity Coefficients on Computed Satellite Orbits and Geodetic Parameters," R.J. Anderle, C.A. Malyevac, and H.L. Green Jr., Journal of Spacecraft and Rockets, Vol 6, Pages 951-954, August 1969

The values in current use are contained in a confidential report.[4] Dr. Hill described what he believes to be the principle limitation of modeling the gravitational coefficients for the 12 hour orbit. The errors due to the harmonic terms, ie, those terms whose order are divisors of the orbit period, will be amplified in the solution. Thus it may be necessary to include these terms in the real time estimation rather than to treat them as parameters which are calibrated independently.

Pole Position Estimates

NWL includes in each 48 hour orbit determination estimates of the X and Y components of the pole position. Analysis of satellite observations over several years have indicated that the use of pole motion determined from astronomical results and available through the International Polar Motion Service can introduce errors of several meters in geodetic position determinations. NWL now includes an estimate of the X and Y components in each 48 hour orbit determination, and publishes the results on an annual basis.[5] Reference 5 indicates that the current process results in a typical standard error in pole position for a 5-day mean of 20 cm.

Reference Material

A bibliography of NWL publications on satellite geodesy is attached. Copies of those items marked with a star were obtained and are available in the DNSDP Reference File.

J. T. Witherspoon

J. T. Witherspoon

/sc

Attachments

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[4]NWL-9B Geodetic Solutions (U) Chen, Martin and Smith, NWL TR2555, April 1971 (Confidential).

[5]Pole Position for 1972 Based on Doppler Satellite Observations, R.J. Anderle, NWL TR2952, May 1973.

6.4 ELM

The following data refers to existing ELM facilities.

PHILCO Ford

Intra Company

28 January 1974

TO: J. T. Witherspoon

FROM: D. E. Westby

SUBJECT: Trip Report - Elmendorf Air Force Base, Anchorage, Alaska

Persons Contacted:

Alaska Air Command -

	Phone Numbers
E. A. Reinikka - Deputy Base Civil Engineer	754-1227
E. Smitty Bruntzel - Logistics Manager	753-1150

1931st Communications Group -

Col. M. J. Anderson - Commander	752-2221
Col. J. R. Stormes - Deputy Commander	752-9221
Lt. Col. W. I. Blanton - Chief Programs Division	752-9288
Maj. T. R. Cook - Chief Engineering	753-4174
Maj. E. W. Place - Chief Maintenance Division	753-1171
G. Connell - Chief Civil Engineering Division	753-0211
J. A. Movius - Chief Civil Engineer	753-7185
H. F. Gallagher - Chief Administration Unit	752-5284

Defense Communications Agency (DCA) Alaska -

Commander J. W. Sachtijen, USN - Commander	754-0121

1. Purpose - The purpose of the subject trip was to obtain information regarding the location of the Globial Positioning System (GPS) Upload and Monitor Station at Elmendorf Air Force Base.

2. Background - Elmendorf Air Force Base is the host activity for many Department of Defense components and agencies. Alaska Command has its Headquarters here, and one of its functions is to provide support of forces throughout Alaska. The Alaska Air Command (AAC) is the top USAF command, and all USAF base activities supports this command. The AAC assigns real estate to the various tenant activities. As far as could be determined there has been no official request for obtaining the use of facilities for the GPS. Lt. Col. Blanton phoned Lt. Col. Jessen's office in Los Angeles and received a verbal request (to be confirmed by message) to assist in finding facilities to meet GPS requirements.

3. Facilities - Elmendorf is a very active air base and space for additional activities is at a premium. The search for an ULS site narrowed down to two possible locations. See Figure 1 attached.

a. The 1931st Communications Group are presently planning to build a Satellite relay station on the Northeast corner of the base. They have a target date to complete the station within nine months after start of construction. However, although their plan and design stage is almost complete, no construction funds have been approved for the project. Their planned station would consist of an antenna and pedestal, power substation with an emergency diesel engine, 2 mobile vans with racks of equipment and a 100 pair communications cable from the site to the Communication building.

This site could be utilized to locate the GPS Update Station (GLS). The site is particularly desirable as far as RFI and obscura effects are concerned. A ridge between the site and the remainder of the base facilities, including air field radars, beams, etc., provides shielding from any interferring affects. There is one mountain peak just at the maximum limit of 5 degrees elevation. The power substation is designed to provide 200 kw of which over 75 kw would be excess to the relay station requirements. Since there are presently no buildings, [illegible]on of the ULS here would require either use of equipment van[illegible]imilar to the Annette Island/MTS Guam sites, or new construct[illegible]oth would probably require use of electric heating.

Thus, the excess 75 kw would undoubtably be required for the ULS. One additional disadvantage is the remoteness of the location, in that Civilian Operators would have to travel a considerable distance for existing housing facilities. This would probably be no disadvantage, if the ULS was made a blue suit operation.

b. The second location considered suitable for locating the ULS is in an existing building No. 35-750 on U.S. Army Fort Richardson. The building is a reinforced concrete structure with an associated power house. There is adequate heating, air conditioning, lighting, office space, and equipment space. The 1931st Communications Group presently uses the building for their VHF transmitter equipment. Over 2500 sq. feet of floor area is clear of all equipment. See Figure 2 attached. The ULS transmitting antenna could be located on the roof of the building, which is approximately 45 feet high. The Air Force is in process of removing a 650 kw Diesel Engine-motor-generator unit from the Power House building, and replacing it with a 200 kw set. Present load is approximately 50 kw peak. Communications circuits between this site and Elmendorf has a large spare capacity, and it is considered ULS requirement could be handled without need for additional cabling. The location of the site is close to all housing requirements that might be needed. The only disadvantage which could be determined in locating the ULS at this site is the obscura caused by two mountain peaks at bearings of approximately 88^{o} and 134^{o} (true). The obscura angles were 6^{o}-0", and 6^{o}-15" respectively taken from the top of the building. The transit was approximately 49 feet above the ground level.

In addition, the mountain at the bearing of 88° has a "Nike" missile site located on the top. The site is approximately four miles (straight line) away from building No. 35-750. Although, the "Nike" site would be in the path of the ULS transmitted beam, it is considered that a radiation hazard to personnel or electro-explosive devices would not exist (Reference: AFM 127-100 Explosive Safety Manual).

4. Grounding - Soil conditions in and around Elmendorf consist of typical glacier gravel deposits. The top soil is 1 to 2 feet of salty, sandy material, while below it is relatively clean sandy gravel with cobbles 4 to 6 inches in diameter.

   Water table in area of building 35-750 on Fort Richardson varies between 2 and 4 feet below the surface. The general opinion at Elmendorf is that a 5-ohm ground condition is excellent, however, no scientific study of ways to improve this situation, if possible, has been carried out. No formal drawings of a ground system could be obtained.

5. Boresight - Both proposed sites are in relatively flat land locations within a distance of 1 mile. The Elmendorf site, however, has small hilly rises (25 to 35 feet) within this area. The Fort Richardson site is flat up to about 2 miles away.

6. Communications - The following comments were received to specific questions:

   a. Additional lines would have to be leased for link to the lower 48 states.

   b. A multiplexer and/or modems can be added to comm links, provided 2400 baud rate is not exceeded.

   c. Any additional cabling can be added, if required, between comm area and ULS site.

   d. Comm path to Elmendorf is shown in attached map. See Figure 3.

7. Maintenance and Logistics Support - Existing support requires all present personnel; however, base can handle ULS support if additional personnel is authorized by AF. Servo maintenance is not presently accomplished by base personnel.

8. Timing - Bureau of Standards unit is located at Elmendorf, in addition to USAF PMEL timing standard equipment. Timing support for the ULS could be worked out, if desired.

9. Documentation - The following documentation materials were obtained and are available from the undersigned:

   a. Brochure of Elmendorf Air Force Base, Anchorage, Alaska.

   b. Alaska Air Command Master Base Plan, Elmendorf (contains contour lines) 8 sheets.

   c. Equipment Floor Plan, building 35-750, Elmendorf AFB.

   d. DCA, Alaska Communications Link Drawing.

   e. Elmendorf AFB drawing (2 sheets).

   f. Joint Operations Graphic (air), Anchorage, Alaska Area.

10. Summary - The Fort Richardson site, building 35-750, is considered an ideal facility for the ULS, provided the 6 degrees obscura is acceptable. Minimum preparation of the location is required.

D. E. Westby

D. E. Westby

/blm

Attachments Figure 1 - Elmendorf Air Force Base Plot Plan
Figure 2 - Main Floor Plan Building 35-750, Fort Richardson
Figure 3 - DCA, Alaska

cc: R. Bryan
J. Carroll
S. Crawford
R. Crum
G. Hickcox
K. Hornberg
D. Middlebrook
H. Stern
J. Thornton

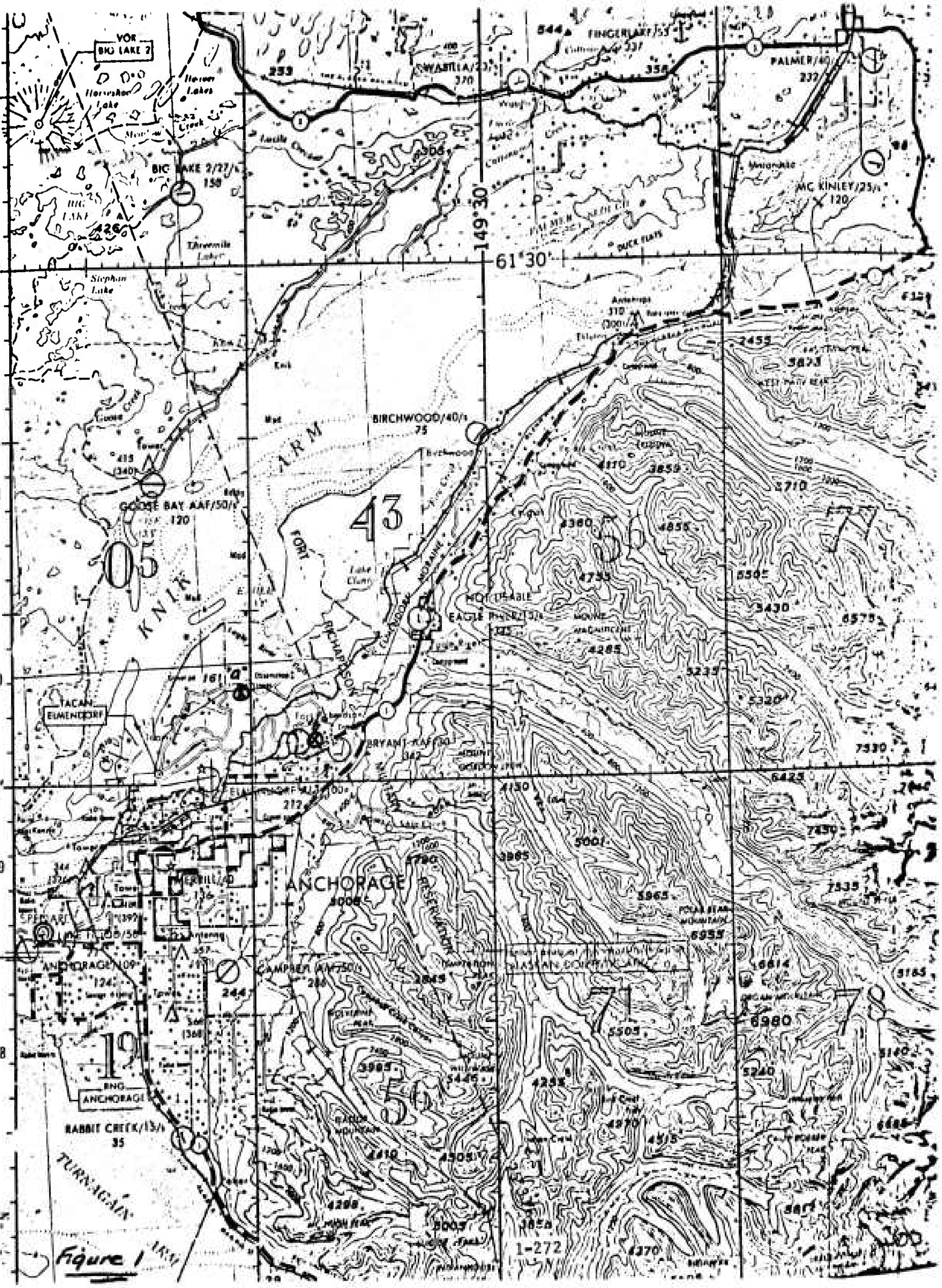
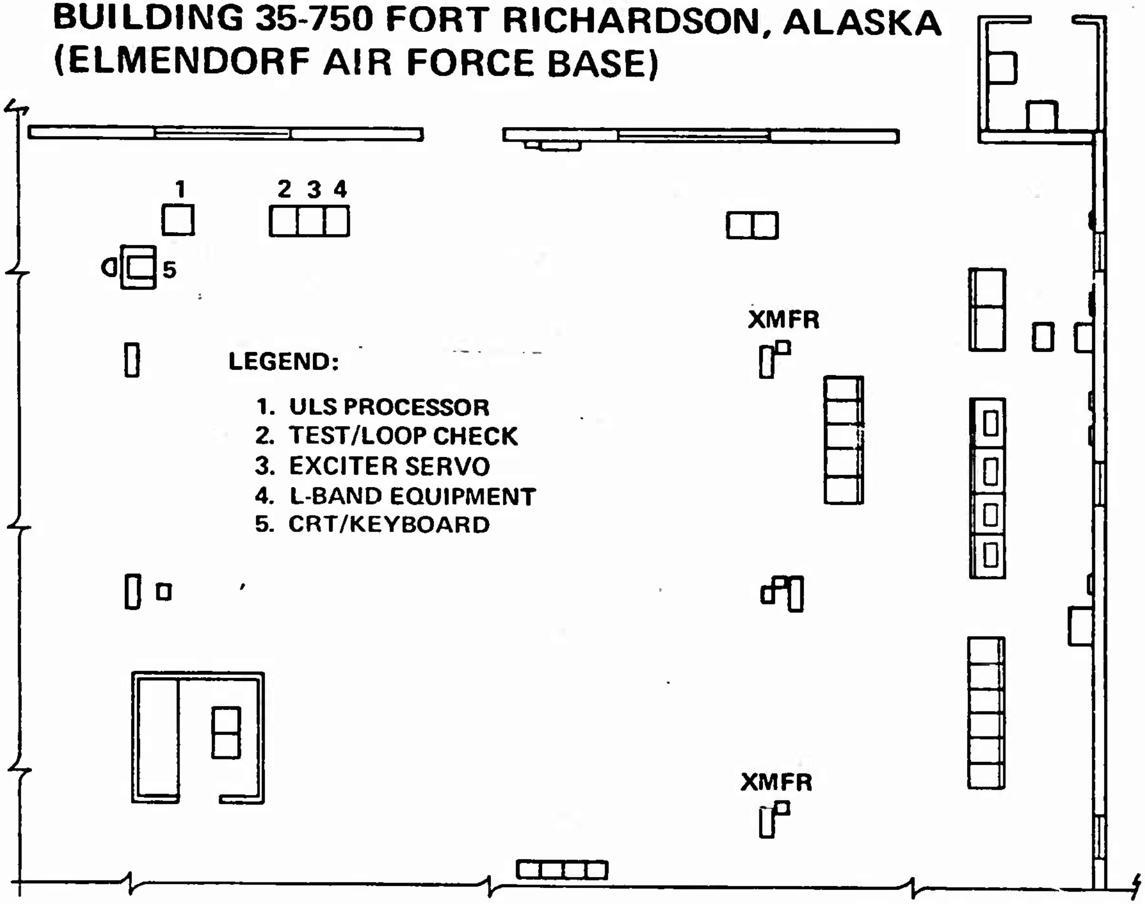

VOR
BIG LAKE 2
BIG LAKE 2/27/L
158
FINGERLAKE/53
PALMER/40
232
MC KINLEY/25/L
120
149°30'
61°30'
BIRCHWOOD/40/L
75
GOOSE BAY AAF/50/L
120
KNIK
ARM
FORT
RICHARDSON
43
05
56
77
TACAN
ELMENDORF
BRYANT AAF
ANCHORAGE
MERRILL
CAMPBELL
71
78
19
56
RBN
ANCHORAGE
RABBIT CREEK/13/L
35
TURNAGAIN
1-272

Figure 1

TYPICAL ARRANGEMENT OF UPLOAD STATION RACKS
BUILDING 35-750 FORT RICHARDSON, ALASKA
(ELMENDORF AIR FORCE BASE)



PHILCO Ford

Figure 2.

DCA — ALASKA LINK DRAWING — AREA 9

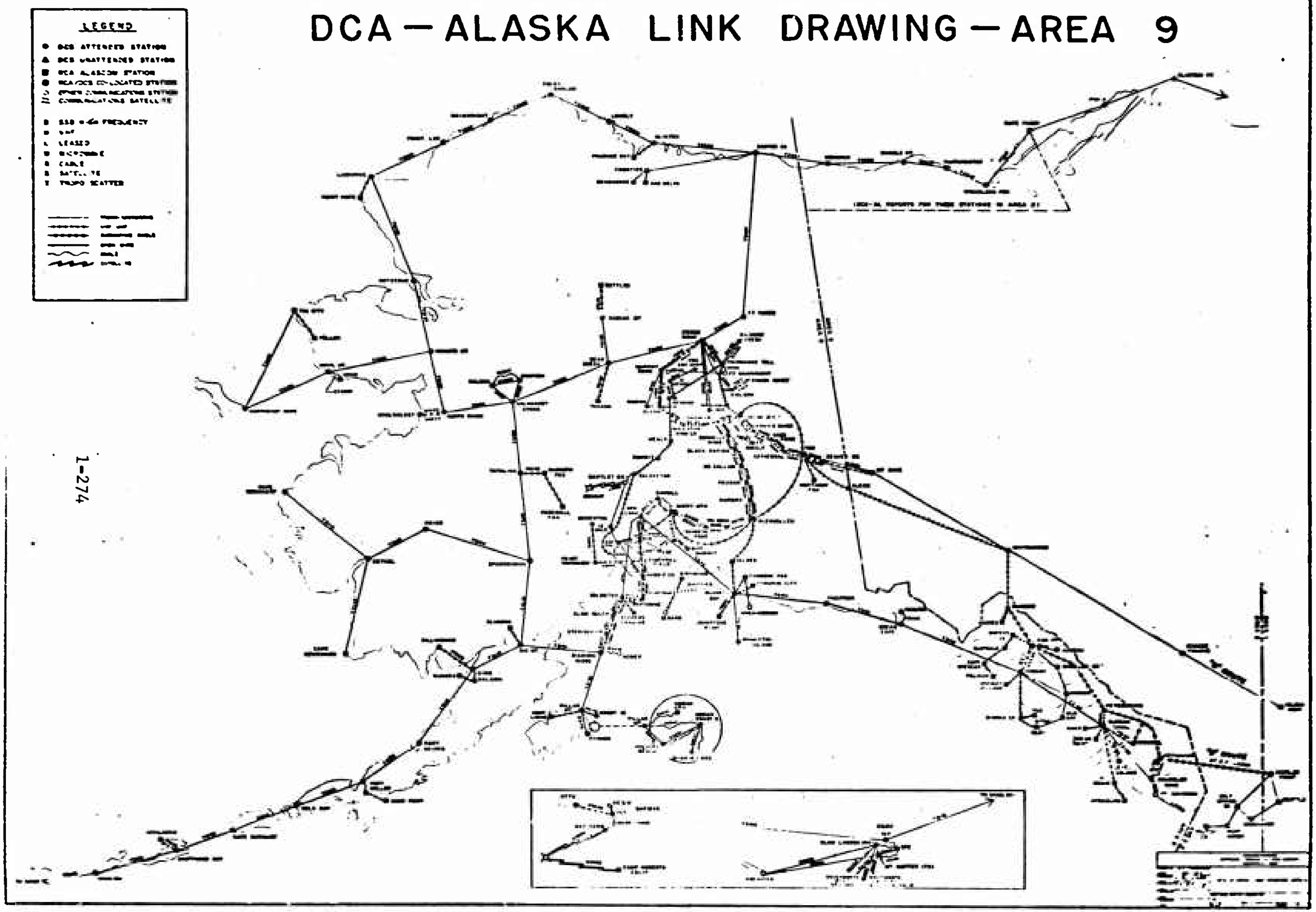


Figure 3 -

7.0 EFFECT OF CONFIGURATION ON ACCURACY

The initial analysis of configuration alternatives investigated the effect of the different configurations on the Ephemeris contribution to the Users Equivalent Range Error (UERE). The first memorandum discusses the variation in accuracy for the first set of configurations considered: SCF-1, SCF-2, SAC, NAG (TRANET) and NWL. The next memorandum addresses the same Control Segment configurations, but with an improved orbit configuration. The last extends the observation span from 24 hours to 48 hours and considers the relocation of the Hawaii Monitor Station to Guam.

PHILCO

Intra Company

November 28, 1973
DNSDP-ARM-001

TO: D. G. Middlebrook

FROM: A. R. Miller

SUBJECT: Alternate Station Configurations

The following report discusses the results from the utilization of the five alternate station configurations. The covariance analysis mode of the TRACE program was run for each of the configurations.

Table 1 summarizes the results found by comparing user position uncertainties and orbit determination accuracies. The value of σ_T is equal to $\sqrt[4]{\sigma_1 \ \sigma_2 \ \sigma_3 \ \sigma_4}$, where $\sigma_N = 1, 2, 3, 4$ are the RSS positional errors of the vehicles, thus allowing for a convenient means to compare the various station configurations. The values of σalt, σlat, and σlong are the user position uncertainties. All of the above mentioned uncertainties are measured in feet. The results indicate that the various station configurations do not have any significant impact on the user's uncertainties or satellite positional errors.

Assumptions

The following assumptions were made in this effort:

1) Orbit Configuration (Delta)

2 x 2 system with the following elements for vehicle #1:

Semi major axis, a = 87,304,082 ft Rt Ascen, $\Omega = 217^\circ$
Eccentricity, e = .0001 Argument of Perigee, w = 0
Inclination, i = 63° M = 0

The remaining satellites have 40° separation in mean anomaly, the second orbit plane is 120° west ($\Omega = 97$) and the phasing between planes is 90°. There is a 4 hour in view time over Holoman and a high spike in GDOP associated with this orbit configuration.

2) Tracking Network

Five station groups were used to gather the tracking data.

Configuration 1 SCF 1

Station	Lat	Long	Ht	
BOS	42.95	288.37	0.	
GUM	13.62	144.86	0.	
HUL	21.56	201.76	0.	
KOD	51.60	207.82	0.	
VTS	34.83	239.50	0.	(Master)

Configuration 2 SCF 2

Station	Lat	Long	Ht	
IOS	-4.67	55.48	0.	
GUM	13.62	144.86	0.	
HUL	21.56	201.76	0.	
KOD	57.60	207.82	0.	
VTS	34.83	239.50	0.	(Master)

Configuration 3 SAC

Station	Lat	Long	Ht	
SPO	47.58	242.33	0.	
LOR	44.82	293.05	0.	
HUL	21.56	201.76	0.	
GUM	13.62	144.86	0.	
SAC	41.33	264.00	0.	(Master)

Configuration 4 TRANET

Station	Lat	Long	Ht	
MUG	34.08	240.83	0.	
MIN	44.75	266.83	0.	
LOR	44.82	293.05	0.	
HUL	21.56	201.76	0.	
VTS	34.83	239.50	0.	(Master)

Configuration 5 NWL

Station	Lat	Long	Ht	
VIR	38.50	283.78	0.	
RIC	25.50	279.50	0.	
YUM	32.58	245.33	0.	
SAM	14.28	189.30	0.	
VTS	34.83	239.50	0.	(Master)

For each of the five configurations a user location was designated. A site at Holoman was chosen with Lat 33.00, Long 254.00 and Ht 0.

3) Measurement Type

Range data with a standard deviation of 10 feet for random errors was assumed. All standard deviations were the same for each configuration so that a valid comparison of results could be obtained.

4) Observation Span and Data Rate

A 24 hour observation span with an interval between observation sets (one measurement from each tracker to each satellite) of $\frac{1}{2}$ hour was chosen. The user took observation data at 24 hours after epoch. The observation span and data rate remained unchanged for all of the station configurations.

5) Parameters Considered in Error

A total of 79 parameters were considered for each of the five runs. The parameters and their respective standard deviations of uncertainty considered in the solution were obtained from a previous TRACE run in the covariance mode. Certain assumptions were made for the user and master station uncertainties as shown below.

Stations

Monitor	Deviation	Master	Deviation
Longitude	11 ft	Latitude	11 ft
Latitude	11 ft	Altitude	20 ft
Altitude	20 ft	Range Bias	10 ft
Range Bias	10 ft		
RB Drift Rate	.0003 ft/sec		
Time Bias	.001 sec		

Since the master station was chosen for its stability and considered the reference station, parameters such as longitude, range bias drift rate and time bias were not considered as unknown p-parameters and therefore did not appear in the solution.

User	Deviation
Long	10000 deg
Lat	10000 deg
Alt	10000 ft
RBIA	10000 ft

Since the user station only takes observation data at the end of the 24 hour span, just the above parameters were considered with high standard deviation of uncertainty.

Discussion of Computer Runs

In general, the alternate station configurations did not have any significant impact on the user's output nor on the orbit determination accuracy for each of the five runs.

The parameter VSB (range bias for vehicle receiving from a station) was tested as an unknown for each satellite. The solution for this parameter in each system configuration showed negligible change. The uncertainty remained at 50' for all cases. The correlations of VSB with each of the satellites position components were relatively high without any significant change due to station configuration. This held true with the comparison of VSB correlations among the satellites, ie, correlations were in the order of .98.

The user uncertainties also were not significantly affected by the change in system configuration as shown in Table 2.

A comparison of the RSS position satellite errors was made at T = 18 hr, 24 hr (time of observation) and 30 hrs after epoch. The spectrum of position error was primarily from 60 ft to 80 ft. The station configuration had no appreciable effect on the satellite position error. The errors are shown in Table 3.

The higher RSS satellite position error associated with the TRANET configuration may be attributed to the lack of a tracking station far out in the Pacific, such as GUM or SAM.

A. R. Miller

A. R. Miller

SUMMARY OF EFFECTS OF ALTERNATE STATION CONFIGURATIONS

		SCF 1	SCF 2	SAC	TRANET	NWL
User Errors at T=24 hrs.	$\sqrt{\sigma_{Long}\sigma_{Lat}}$	20.6	22.35	18.8	18.6	17.3
	σ_{Alt}	30.2	32.9	29.8	27.9	24.8
Sat Ephem Errors	σ_T at T=24 hrs	63.7	62.7	63.7	69.8	67.9
	σ_T at T=30 hrs	71.7	70.5	71.9	83.1	78.0

TABLE 1

SUMMARY OF USER (HOL) UNCERTAINTIES
WITH VTS (SAC) AS MASTER STATION

		SCF 1	SCF 2	SAC	TRANET	NWL
HOL	Long (ft.)	40.15	45.99	39.42	37.23	33.94
	Lat (ft.)	10.54	10.87	10.11	9.34	8.83
	Alt (ft.)	30.22	32.94	29.75	27.87	24.76
	RBIA (ft.)	35.75	40.04	35.06	33.11	29.79
VTS *(SAC)	Lat (ft.)	4.81	4.89	* 4.67	4.85	4.78
	Alt (ft.)	6.78	6.56	* 6.97	6.96	6.40
	RBIA (ft.)	5.70	5.87	* 5.69	5.43	5.46

TABLE 2

RSS SATELLITE POSITION ERROR

		SCF 1	SCF 2	SAC	TRANET	NWL
σ_1 (ft.)	T=18 hrs	64.42	61.81	64.20	71.72	66.77
	T=24 hrs	71.67	66.46	70.14	79.43	74.89
	T=30 hrs	75.88	70.76	74.40	92.02	83.86
σ_2 (ft.)	T=18 hrs	62.35	62.92	63.31	67.29	63.94
	T=24 hrs	62.65	64.91	62.92	65.53	64.61
	T=30 hrs	69.83	72.43	70.78	75.65	73.54
σ_3 (ft.)	T=18 hrs	60.45	59.65	59.88	64.16	61.41
	T=24 hrs	58.94	58.19	59.19	67.60	65.94
	T=30 hrs	69.81	67.57	69.85	83.20	77.43
σ_4 (ft.)	T=18 hrs	61.38	61.11	61.32	66.10	64.01
	T=24 hrs	62.21	61.52	62.88	67.64	66.53
	T=30 hrs	71.58	71.31	72.55	82.28	77.54

TABLE 3

PHILCO Ford

Intra Company

January 10, 1974
GPS-ARM-003

TO: D. G. Middlebrook

FROM: A. R. Miller

SUBJECT: Comparison of Four Control Segment Alternatives

This memo documents results found in past computer runs designed to compare effects of four different station configurations. The covariance analysis mode of the TRACE program was run for each of the configurations.

Table 1 summarizes the results by comparing user position uncertainties and orbit determination accuracies. The numerical values for Table 1 are expressed in feet. The following expressions define the tabulated errors:

$$\sigma_u = \sqrt{\sigma^2_{LONG} + \sigma^2_{LAT} + \sigma^2_{ALT}}$$, user error at the end of the 24-hour observation

$$\sigma_T = \sqrt[4]{\sigma_1\ \sigma_2\ \sigma_3\ \sigma_4}$$, satellite ephemeris error at the end of the 24-hour observation span

Summary of Effects of Alternate Station Configurations

	SCF	SAC	NAG	NWL
σ_u	16.8	20.9	15.8	20.9
σ_T	66.3	82.9	69.4	79.6

TABLE 1

The purpose of these runs was to determine the relative differences in user accuracies among the various station configurations. Therefore, the same assumptions were made for each station configuration in order to obtain a valid comparison. As indicated in Table 1, the SCF and NAG networks provided better user accuracies as compared to the NWL and SAC networks. Further discussion of the differences is given at the end of this memo.

Assumptions

Although the following assumptions reflect old initial conditions, parameters and sigmas, the overall comparison of accuracies and their respective differences was of prime concern since the assumptions remained unchanged for each station configuration.

1. Orbit Configuration (Theta)

   2 x 2 system with the following elements for vehicle #1:

   Semi-major axis, a = 87,304,082 ft. Rt Ascen, = 165°

   Eccentricity, e = .0001 Argument of Perigee, W = 0

   Inclination, i = 63° M = 70°

   The remaining vehicles differ in mean anomaly and right ascension only as indicated below.

	Vehicle 2	Vehicle 3	Vehicle 4
Right Ascension	165°	45°	45°
Mean Anomaly	119°	85°	122°

2. Tracking Networks

   Four station groups were used to gather the tracking data.

Configuration 1 SCF

Station	LAT	LONG	HT	
BOS	42.95	288.37	0	
HUL	21.56	144.86	0	
KOD	51.60	207.82	0	
VTS	34.83	239.50	0	(Master)

Configuration 2 SAC

Station	LAT	LONG	HT	
SPO	47.58	242.33	0	
LOR	44.82	293.05	0	
SAC	41.33	264.00	0	(Master)

Configuration 3 NAG

Station	LAT	LONG	HT	
HUL	21.56	201.76	0	
MIN	44.75	266.83	0	
LOR	44.82	293.05	0	
MUG	34.08	240.83	0	(Master)

Configuration 4 NWL

Station	LAT	LONG	HT	
SAM	-14.28	189.30	0	
YUM	32.58	245.33	0	
RIC	25.50	279.50	0	
VIR	38.50	283.78	0	(Master)

For each of the four configurations a user location was designated. A site at Holloman was chosen with Lat 33.00, Long 254.00 and Ht 0.

3. Measurement Type

Range data with a standard deviation of 10 feet for random errors was assumed. All standard deviations were the same for each configuration.

4. Observation Span and Data Rate

A 24 hour observation span with an interval between observation sets (one measurement from each tracker to each satellite) of 1/2 hour was chosen. The user took observation data upon the end of the 24 hour observation span and one hour after the observation span.

5. Parameters Considered in Error

A total of 73 parameters were considered for each of the four runs. All parameters were designated as P-parameters. Certain assumptions were made for the user and master station uncertainties as shown below.

Stations

Monitor	Deviation	Master	Deviation
Longitude	11 ft	Latitude	11 ft
Latitude	11 ft	Altitude	20 ft
Altitude	20 ft	Range Bias	10 ft
Range Bias	10 ft		
RB Drift Rate	.0003 ft/sec		

User	Deviation
Long	10000 deg
Lat	10000 deg
Alt	10000 ft

Discussion

In general, the SCF and NAG configurations provided better user accuracies and satellite positional errors than did the SAC and NWL networks. The SAC configuration contained only two minitor stations, thus coverage was not as comprehensive nor distributed as well as the other networks. SAC provided no coverage by a monitor station out in the Pacific ocean, whereas the other configurations included either HUL (Hawaii) or SAM (American Samoa). Although NWL included a monitor station in the Pacific, the west and northwest areas of CONUS were void of a monitor station. Note that the SCF and NAG configurations had their respective monitor stations located in the same general geographical area. Therefore, the SCF and NAG networks provided similar user accuracies since the relative distribution of coverage over CONUS and the Pacific (HUL) was comparable.

As indicated in the assumptions, the Theta orbit was designated for each computer run. The improved GDOP and elimination of the spike encountered with the Delta orbit used in previous runs resulted in increased user accuracies. Table 2 compares user accuracies with similar runs that utilized the Delta orbit.

Comparison of User Accuracies

with the Delta Orbit and Theta Orbit

	SCF Delta	SCF Theta	NAG Delta	NAG Theta
HOL Long (ft)	40.2	4.4	37.2	4.3
Lat (ft)	10.5	9.4	9.3	9.0
Alt	30.2	13.2	27,9	12.3

TABLE 2

The following tables list in detail the results obtained on user accuracy and satellite positional errors for the four station configurations.

Summary of User (HOL) and Master Station Uncertainties

		HOL 1 (at end of Obs. Span)	HOL 2 (1 hr after Obs. Span)	Master Station
	Long	4.43	6.55	VTS
SCF	Lat	9.37	15.66	5.55
σ	Alt	13.21	19.16	7.68
(ft)	RBIA	8.97	10.02	5.94
	Long	5.33	8.28	SAC
SAC	Lat	10.30	18.75	6.15
σ	Alt	17.35	26.36	9.54
(ft)	RBIA	10.32	11.15	6.49
	Long	4.25	6.85	MUG
MAG	Lat	9.04	16.30	5.44
σ	Alt	12.30	19.60	7.90
(ft)	RBIA	8.69	10.09	5.93
	Long	6.16	8.89	VIR
NWL	Lat	12.52	24.70	5.90
σ	Alt	15.56	26.24	7.51
(ft)	RBIA	11.01	14.18	6.42

TABLE 3

Satellite Positional Error

	Vehicle	At End of Obs. Span	1 Hour After Obs. Span
SCF (ft)	1	62.51	66.11
	2	69.64	75.47
	3	66.39	70.43
	4	66.85	72.02
SAC (ft)	1	77.43	85.43
	2	91.83	102.87
	3	84.07	90.85
	4	78.95	87.52
NAG (ft)	1	64.06	68.65
	2	75.27	81.96
	3	69.23	73.66
	4	69.45	75.40
NWL (ft)	1	70.02	75.93
	2	76.24	80.37
	3	99.07	107.28
	4	75.80	82.69

TABLE 4

A. R. Miller

A. R. Miller

tmh

cc: J. Brown
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D. Potter
E. Shaparenko
J. Thiebault
L. Walters
J. Witherspoon

PHILCO Ford

Intra Company

January 16, 1974
GPS-ARM-005

TO: D. G. Middlebrook

FROM: A. R. Miller

SUBJECT: Effects of Expanded Observation Spans and Relocation of Pacific Monitor Station

This memo discusses the effects on the user solution by utilizing a 48 hour observation span as opposed to a 24 hour observation span, and also by replacing the Hawaii monitor station with a station located at Guam. The covariance analysis mode of the TRACE program was run for each case.

Table 1 summarizes the results found by comparing user positional accuracies and satellite positional errors. The values obtained for the table are defined below.

$$\sigma_u = \sqrt{\sigma_{long}^2 + \sigma_{lat}^2 + \sigma_{alt}^2} \; ,$$ one hour after start of test over Holloman

$$\sigma_t = \sqrt[4]{\sigma_1 \cdot \sigma_2 \cdot \sigma_3 \cdot \sigma_4} \; ,$$ one hour after start of test over Holloman

The user positional errors are represented by σ_{long}, σ_{lat} and σ_{alt}, and the satellite positional errors by σ_1, σ_2, σ_3, σ_4.

The table indicates that the user accuracies were improved by approximately a factor of 2 by replacing the monitor station located at Hawaii with one located farther out in the Pacific on Guam. The utilization of 48 hours of observation data as opposed to 24 hours of observation data increased user accuracies by approximately a factor of 4. There was substantial improvement of satellite positional errors with 48 hours of observation data, and also from replacing the HUL monitor station with the GUM monitor station.

Summary of Results

	24 hrs of Obs (HUL in network)	24 hrs of Obs (GUM in network)	48 hrs of Obs (HUL in network)
σ_u (ft)	95.7	45.3	20.8
σ_t (ft)	84.1	60.9	41.7

TABLE 1

Assumptions

The latest ephemeris error analysis baseline was used in this effort.

1) Orbit Configuration (Sigma)

2 x 2 system with following elements for vehicle #1:

Semi major axis, a = 87,145,102 ft Rt. Ascen., = 195°
Eccentricity, e = .0001 Argument of Perigee, w = 0
Inclination, i = 63° M = 41° CPAW = 10^{-9}

The other vehicles differed in mean anomaly and right ascension of node as shown below.

	Veh 2	Veh 3	Veh 4
Rt. Ascen.	195°	75°	75°
Mn. Anom.	81°	64°	124°

2) Tracking Network

The SCF Configuration

Station	Lat	Long	Ht	
BOS	42.95	288.37	0.	
KOD	51.60	207.82	0.	
HUL	21.56	201.76	0.	
VTS	34.83	239.50	0.	(Master)

GUM with Lat 13.62, Long 144.86, and Ht 0. was substituted for HUL in the SCF configuration.

For each of the computer runs a user locations was designated. A site at Holloman was chosen with Lat 33.00, Long 254.00 and Ht 0.

3) Observation Span and Data Rate

A 24 hour observation span with an interval between observation sets of 15 min was used with the SCF configuration and with the configuration which included the GUM monitor station. A computer run was also made with a 48 hour observation span at 15 min intervals for the SCF configuration. The observation stop time was two hours prior to start of test over Holloman; the user observation data was taken one hour after start of test over Holloman.

4) Measurement Type

Range data with a standard deviation of 5 feet for random errors was assumed.

5) Parameters Considered in Error

The latest baseline P and Q parameters and associated sigmas were used. The station location errors are shown below.

Monitor	Type	Deviation	Master	Type	Deviation
Longitude	Q	10 ft	Latitude	Q	10 ft
Latitude	Q	10 ft	Altitude	Q	10 ft
Altitude	Q	10 ft			
Range Bias	P	50 ft			
RB Drift Rate	P	.0003 ft/sec			

User	Type	Deviation
Long	P	10000. deg
Lat	P	10000. deg
Alt	P	10000. ft
RBIA	P	10000. ft

Two terms for the gravity model errors were included as Q parameters as shown below.

Term	Sigma
$J_{2,2}$	$.05 \times 10^{-6}$
$J_{3,2}$	$.02 \times 10^{-6}$

The solution state vector included the station monitor clocks (RBIA, RBD) and the following P-parameters.

Parameters	Sigma
Orbit elements (FG set)	
AF, AG	1×10^{-5} radians
N	1×10^{-8} deg/sec
L	1×10^{-3} degrees
CHI PSI	1×10^{-5} radians
CPAW	15%
Satellite Clocks	
Offset (VSB)	100 ft
Drift Rate (VSBD)	.0006 ft/sec

<u>Discussion</u>

The increased accuracy obtained by using a 48 hour observation span as opposed to a 24 hour observation span as indicated before was of a magnitude of four times greater. High uncertainties were found among user solution parameters and monitor station location parameters in the DPDQ-sigma (Q) matrix for 24 hours of observations. The errors associated with HOL Alt, and KOD Alt and KOD Long were 14 ft and 50 ft respectively; with HOL RBIA and the same KOD parameters the errors were 4.2 ft and 23.1 ft. The uncertainties were greatly reduced with a 48 hour observation span. The errors associated with HOL Alt, and KOD Alt and KOD Long were only .7 ft and 1.8 ft; with HOL RBIA and the same KOD parameters the errors were .4 ft and 1.5 ft.

The expanded observation span decreased the satellite positional errors by a factor of two. The values are compared in Table 3.

By replacing the HUL monitor station with a station at Guam, the user errors were decreased by approximately a factor of two. The GUM monitor station provided better distribution of satellite coverage for the station configuration. The observation data indicated that the configuration with HUL as a station did not have satellite 3 in view for approximately 8 hours prior to the end of the observation span. The better coverage was also reflected in the reduction of satellite positional errors. For example, the positional error for vehicle #3 was 106 ft with HUL as a monitor station and only 51 ft with GUM as a monitor station.

Tables 2 and 3 list the results obtained on user accuracies and satellite positional errors. Table 4 lists the errors associated with the satellite clock offset (VSB).

A. R. Miller

A. R. Miller

tmh

User Accuracies

	24 hrs of Obs. (HUL in network)	24 hrs of Obs. (GUM in network)	48 hrs of Obs. (HUL in network)
σ_{long} (ft)	46.0	19.6	12.2
σ_{lat} (ft)	18.5	11.2	6.5
σ_{alt} (ft)	81.8	39.3	15.5
σ_{RBIA} (ft)	42.9	24.9	9.7

TABLE 2

Satellite Positional Errors

	24 hrs of Obs. (HUL in network)	24 hrs of Obs. (GUM in network)	48 hrs of Obs. (HUL in network)
Veh #1 (ft)	82.0	64.3	37.0
Veh #2 (ft)	78.8	64.1	42.6
Veh #3 (ft)	106.3	51.0	40.4
Veh #4 (ft)	72.8	65.6	47.3

TABLE 3

Satellite Clock Offset Errors

	24 hrs of Obs. (HUL in network)	24 hrs of Obs. (GUM in network)	48 hrs of Obs. (HUL in network)
VSB #1 (ft)	18.8	15.5	8.1
VSB #2 (ft)	15.9	14.1	8.9
VSB #3 (ft)	40.3	21.9	7.9
VSB #4 (ft)	15.4	13.9	8.1

TABLE 4

REPORT C 2

ORBIT CONFIGURATION SELECTION

REPORT C 2

ORBIT CONFIGURATION SELECTION

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REPORT C 2

ORBIT CONFIGURATION SELECTION

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ORBIT CONFIGURATION SELECTION

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1.0 SCOPE

The objective of this trade study is to determine the optimum orbit for each of the GPS phases. Factors considered during Phase I are GDOP and time-in-view at White Sands Missile Range (WSMR) Satellite Elevation angle, station keeping requirements and Upload Time provided. Factors considered during Phase IIA are GDOP and continuous time in view of 4 satellites at WSMR. Phase IIB considered the requirement to provide 2 satellites coverage worldwide. Phase III, the operational phase, finally requires 4 useable satellites on a global basis.

1.1 BASELINE ORBIT CONFIGURATION SUMMARY

Phase I Baseline. The orbital parameters of the selected Phase I baseline orbit configuration, SIGMA, are listed in Table 1. This configuration provides a test time at White Sands Missile Range (WSMR) of 2 hours 25 minutes with an average GDOP of 4.2. The maximum GDOP during the test period is less than 7 and the trailing satellite is in view of the Vandenburg Upload Station 19 minutes before the test period begins. The ground track of this orbit is shown in Figure 1 and the variation of GDOP during the test period is shown in Figure 2. A polar plot of the azimuth and elevation angles of the four satellites from WSMR is shown in Figure 3. The time-in-view bargraphs for this configuration are shown in Figure 4 for the 17 station locations considered in the Control Segment Configuration Study, Report C1.

It may be noted that the longitudes of the Ascending Node and Eccentric Anomalies listed in Table 1 are different than those cited elsewhere for the baseline SIGMA orbit. The values shown have been altered from those previously given in order to enable a direct comparison of the Phase I and Phase IIA vehicles. The orbits are equivalent (see Appendix B) and the only impact is a shift in absolute epoch time.

TABLE 1

PHASE I - PASELINE CONFIGURATION

(SIGMA)

SATELLITE NUMBER	ARG. OF PERIGEE	ECCENTRIC ANOMALY	ECCEN-TRICITY	INCLINA-TION	LONG. OF ASCENDING NODE	SEMI MAJOR AXIS
1	0	191	0	63	120	14341.5
2	0	231	0	63	120	14341.5
3†	0	214	0	63	0	14341.5
4	0	274	0	63	0	14341.5

Test time over W S M R	145 minutes
View time	145 minutes
Average GDOP during test	4.16
Minimum GDOP	3.8
Tolerances	
Eccentric Anomally	$\pm 6^{o}$
Inclination	$\pm 2^{o}$
Ascending Node	$\pm 2^{o}$
Semimajor Axis	$\pm$ .1 n.mi.
Station keeping requirement	~ 1 ft/sec/yr.
All elevation angles above 15 deg.	75 minutes.

† Trailing NTS-II Satellite

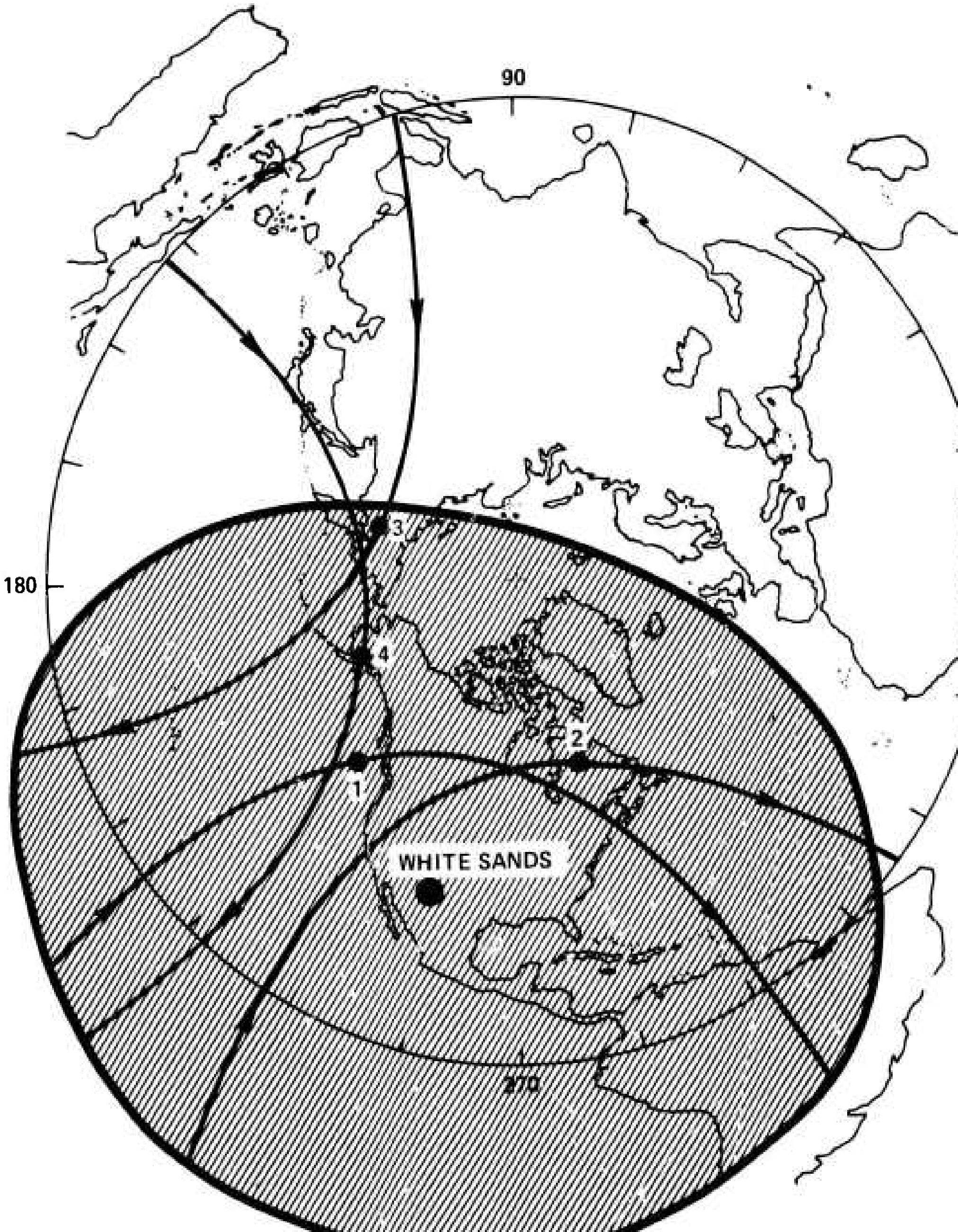


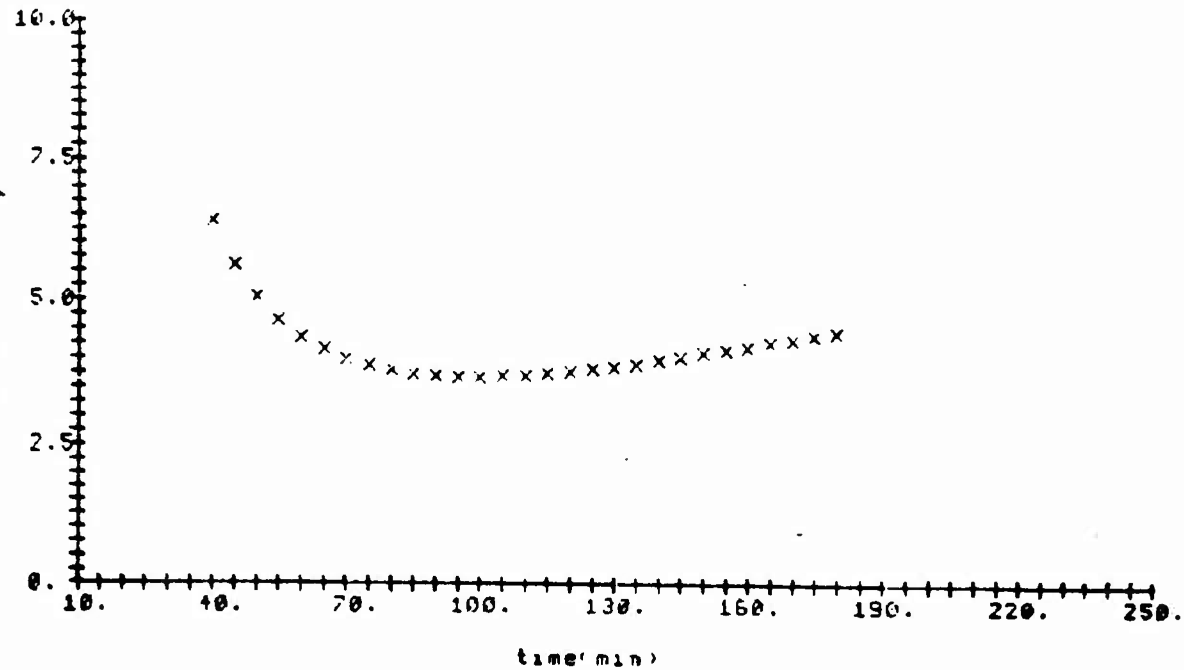
FIGURE 1 Phase I Baseline Configuration SIGMA Orbit Ground Tracks

FIGURE 2 SIGMA GDOP VS TIME

ARGUMENT OF PERIGEE DEG.	ECCENTRIC ANOMALY DEG.	ECCENTRICITY	INCLINATION DEG.	ASCENDING NODE DEG	SEMI MAJOR AXIS NMI
0.	41.0000	0.	63.0000	155.0000	14342.0000
0.	81.0000	0.	63.0000	195.0000	14342.0000
0.	64.0000	0.	63.0000	75.0000	14342.0000
0.	124.0000	0.	63.0000	75.0000	14342.0000

GROUND STATION LONGITUDE -106.0 LATITUDE 33.0 RADIUS 3444.0

time with trace of GDOP below 10 is 29.0x5min, ave. ± of GDOP 4.16



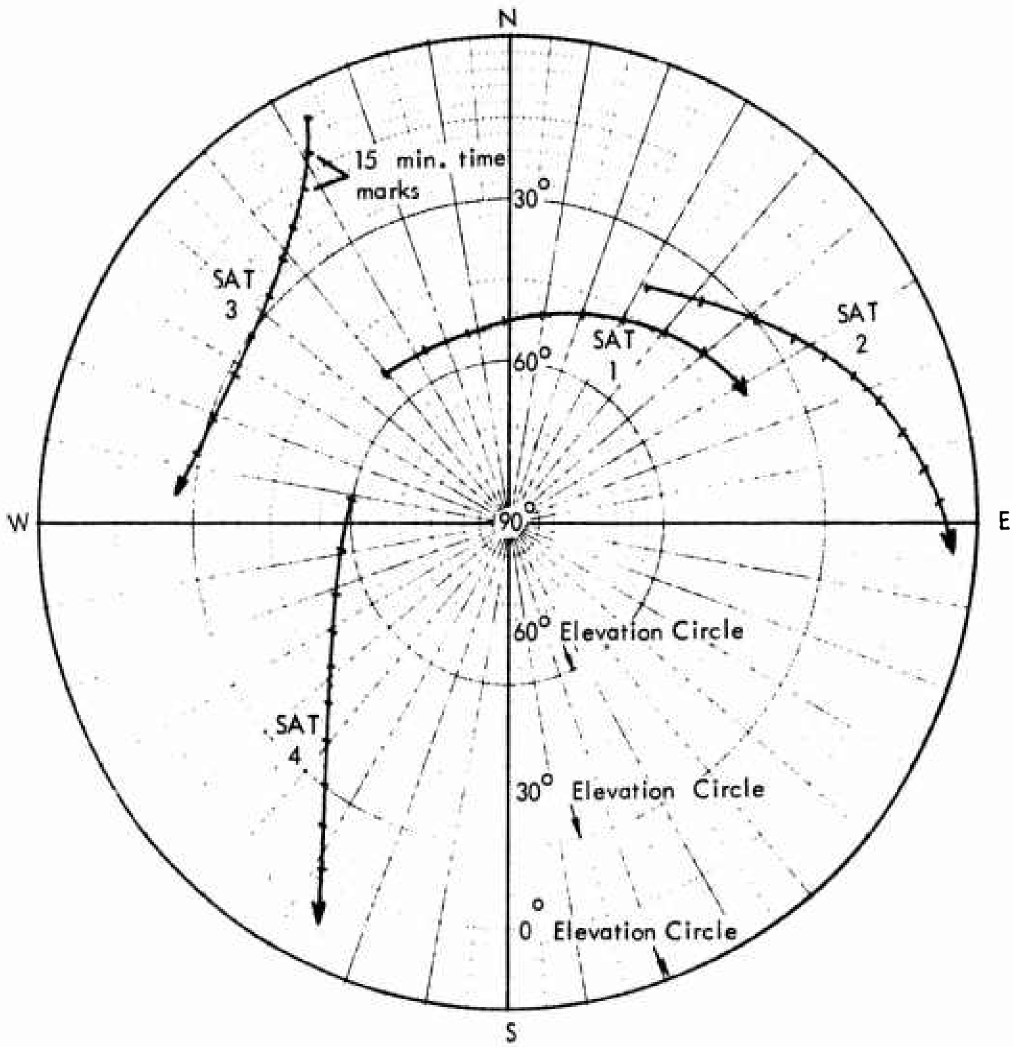


FIGURE 3 Azimuth and Elevation of SIGMA Configuration From WSMR

FIGURE 4 (1 of 2) TIME-IN-VIEW BARGRAPHS (SIGMA)

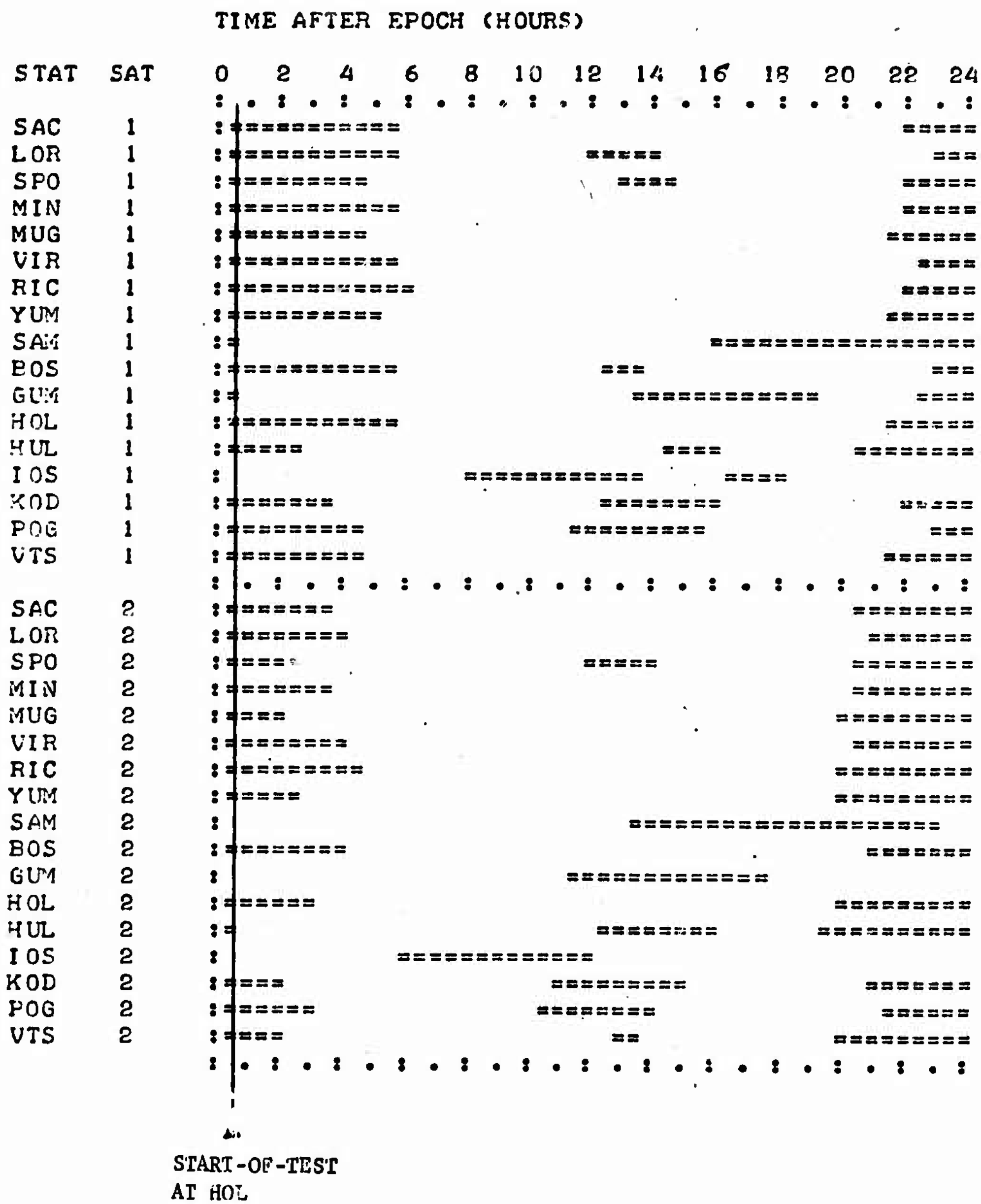


FIGURE 4 (PG 2 OF 2) TIME-IN-VIEW BARGRAPHS (SIGMA)

TIME AFTER EPOCH (HOURS)

The results of this trade study and the baseline orbit selection have an effect upon the NTS space vehicle contractor. Paragraph 3.2.1 of Appendix IV to DNSDP-SVR-101 states the following:

> NTS - The NTS will be the trailing satellite of the constellation. It will transmit the PRN navigation signal until the lead satellite is 5° below the horizon at the test site, at which time it will be switched to transmit the STR navigation signal. The PRN navigation assembly will be reactivated over Guam or Hawaii.

Table 1A below lists the set times for each of the four Phase I satellites at White Sands Missile Range (WSMR) and Hawaii.

TABLE 1A

Set Time After End of Test at WSMR (Hrs:Min)

Site \ Satellite	1	2	3	4
Hawaii	-:42	-2:30	2:46	:33
WSMR	2:18	0	1:18	:04

It can be seen that the selection of NTS satellite is dependent upon where the sidetone ranging tests will be conducted. If the tests are in the Pacific, the NTS should be satellite number 3, while testing at WSMR is optimally accomplished with satellite number 1.

Phase IIA Baseline

The orbital characteristics of the selected Phase IIA baseline configuration, OMEGA-2A are given in Table 2. This orbit is designed to provide a lengthy continuous time-in-view of four satellites at WSMR without GDOP spikes or gaps. Figures 5, 6 and 7 show the time-in-view bargraphs of the 9 satellites for Vandenberg (VTS), Elmendorf/Kodiak (KOD), and WSMR/Holoman (HOL).

TABLE 2

PHASE II-A - BASELINE CONFIGURATION

(OMEGA-2A)

SATELLITE NUMBER	ARG. OF PERIGEE	ECCENTRIC ANOMALY	ECCEN-TRICITY	INCLINA-TION	LONG. OF ASCENDING NODE	SEMI MAJOR AXIS	MANEUV[illegible] FUEL LB. [illegible]
5	0	0	0	63	0	14341.5	-
3	0	45	0	63	0	"	8^+ lb.
4	0	90	0	63	0	"	8^+ lb.
1	0	225	0	63	120	"	2^+ lb.
2	0	270	0	63	120	"	2^+ lb.
6	0	315	0	63	120	"	-
7	0	135	0	63	240	"	-
8	0	180	0	63	240	"	-
9	0	225	0	63	240	"	-

Test time over W S M R	7 hours, 45 minutes.
Minimum GDOP	3
Average GDOP	4
Maximum GDOP	12
Station keeping	~ 1 ft/sec./yr.
All elevation angles above 15°	3 hr. 45 minutes

FIGURE 5 TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= OMEGA-2A
SATELLITE VIEW PERIODS AT VTS
ELEVATION ANGLE GREATER THAN: 5 DEG

TIME AFTER EPOCH (HOURS)

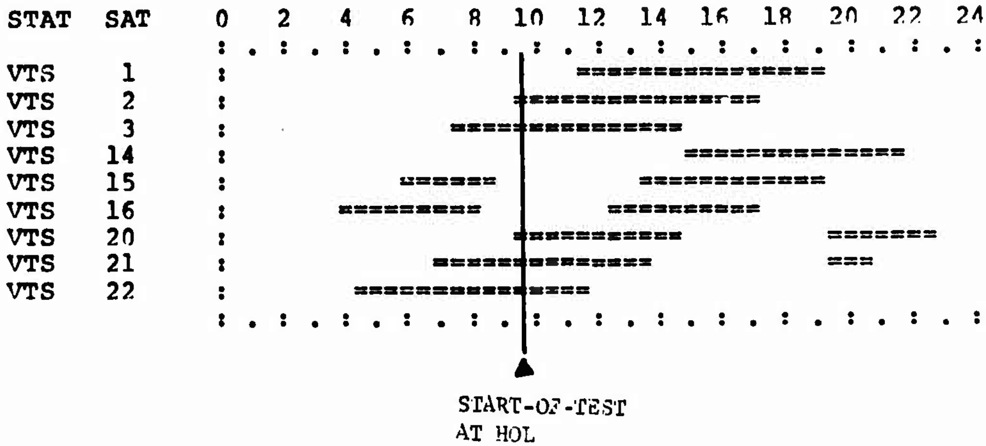


TABLE OF VIEW PERIODS (HOURS AFTER EPOCH)

STAT	SAT	RISE	SET	RISE	SET	RISE	SET	TOT IN	TOT OUT	MAX OUT SEGMENT
VTS	1	11.60	19.08	.00	.00	.00	.00	7.48	16.52	16.517
VTS	2	9.43	17.05	.00	.00	.00	.00	7.62	16.38	16.383
VTS	3	7.65	14.45	.00	.00	.00	.00	6.80	17.20	17.200
VTS	14	15.08	21.50	.00	.00	.00	.00	6.42	17.58	17.583
VTS	15	5.97	8.62	13.63	19.10	.00	.00	8.12	15.88	10.867
VTS	16	4.08	8.08	12.47	17.08	.00	.00	8.62	15.38	11.000
VTS	20	9.48	14.73	19.52	22.57	.00	.00	8.30	15.70	10.917
VTS	21	7.22	13.35	19.38	20.50	.00	.00	7.25	16.75	10.717
VTS	22	4.48	11.72	.00	.00	.00	.00	7.23	16.77	16.767

FIGURE 6 TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= OMEGA-2A
SATELLITE VIEW PERIODS AT KOD
ELEVATION ANGLE GREATER THAN: 5 DEG

TIME AFTER EPOCH (HOURS)

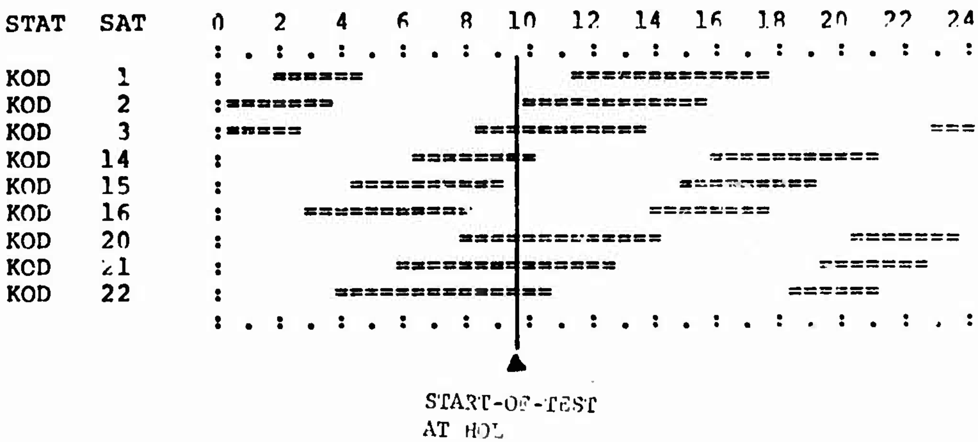


TABLE OF VIEW PERIODS (HOURS AFTER EPOCH)

STAT	SAT	RISE	SET	RISE	SET	RISE	SET	TOT IN	TOT OUT	MAX OUT SEGMENT
KOD	1	1.97	4.50	11.58	17.75	.00	.00	8.70	15.30	8.217
KOD	2	.53	3.53	9.97	15.72	.00	.00	8.75	15.25	8.817
KOD	3	.00	2.58	8.53	13.72	22.88	24.00	8.88	15.12	9.167
KOD	14	6.37	10.23	16.07	21.07	.00	.00	8.87	15.13	9.300
KOD	15	4.63	9.15	14.87	19.23	.00	.00	8.88	15.12	9.400
KOD	16	2.78	7.92	13.82	17.53	.00	.00	8.85	15.15	9.250
KOD	20	8.10	13.95	20.52	23.40	.00	.00	8.73	15.27	8.700
KOD	21	6.07	12.28	19.53	22.67	.00	.00	9.35	14.65	7.400
KOD	22	4.20	10.43	18.37	20.82	.00	.00	8.68	15.32	7.933

FIGURE 7 TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= OMEGA-2A
SATELLITE VIEW PERIODS AT HOL
ELEVATION ANGLE GREATER THAN: 5 DEG

TIME AFTER EPOCH (HOURS)

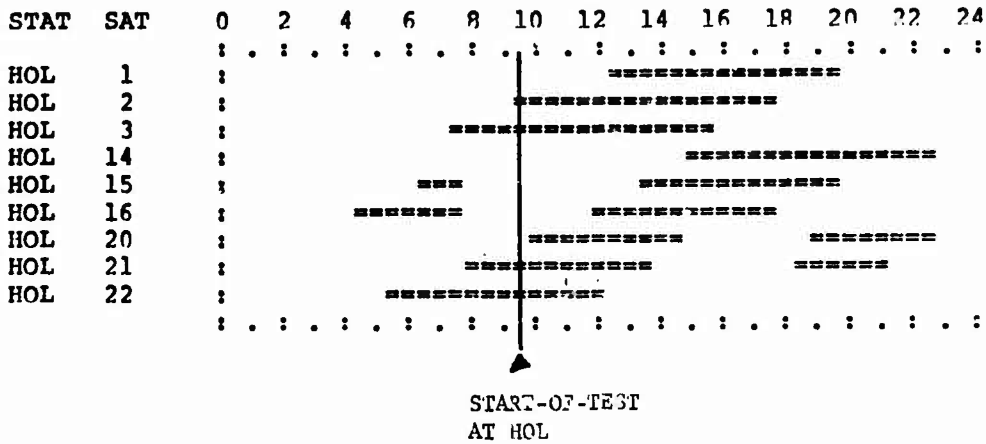


TABLE OF VIEW PERIODS (HOURS AFTER EPOCH)

STAT	SAT	RISE	SET	RISE	SET	RISE	SET	TOT IN	TOT OUT	MAX OUT SEGMENT
HOL	1	12.35	19.33	.00	.00	.00	.00	6.98	17.02	17.017
HOL	2	9.75	17.52	.00	.00	.00	.00	7.77	16.23	16.233
HOL	3	7.73	15.28	.00	.00	.00	.00	7.55	16.45	16.450
HOL	14	15.12	22.37	.00	.00	.00	.00	7.25	16.75	16.750
HOL	15	5.52	7.60	13.50	19.55	.00	.00	7.13	16.87	10.967
HOL	16	4.42	7.53	12.13	17.33	.00	.00	8.32	15.68	11.083
HOL	20	9.87	14.57	18.85	22.73	.00	.00	8.58	15.42	11.133
HOL	21	7.83	13.38	18.43	20.82	.00	.00	7.93	16.07	11.017
HOL	22	5.35	11.90	.00	.00	.00	.00	6.55	17.45	17.450

Phase IIB Baseline

The orbital characteristics of the selected Phase IIB baseline configuration, GAMMA-2B, is shown in Table 3. This configuration provides continuous global coverage by at least two satellites and approximately 14 hours per day coverage by 3 satellites at those locations at 30°N and 30°S latitude locations (see Section 4.0). Exact time-in-view data for upload stations at Vandenberg (VTS) and Elmendorf/Kodiak (KOD) is given in Figures 8 and 9, respectively. Time-in-view bargraphs for all locations considered are given in Figure 10.

TABLE 3

PHASE II-B - BASELINE CONFIGURATION

(GAMMA-2B)

SATELLITE NUMBER	ARG. OF PERIGEE	ECCENTRIC ANOMALY	ECCEN-TRICITY	INCLINA-TION	LONG. OF ASCENDING NODE	SEMI MAJOR AXIS	MANEUVE FUEL LB.
3	0	0	0	63	0	14341.5	10^+
4	0	120	0	63	0	"	10^+
5	0	240	0	63	0	"	6^+
6	0	0	0	63	120	"	2^+
1	0	120	0	63	120	"	7
2	0	240	0	63	120	"	4
7	0	0	0	63	240	"	6
8	0	120	0	63	240	"	3
9	0	240	0	63	240	"	2

Two satellite coverage	24 hours global
Three satellite coverage	14 hours $\pm$ 30 deg. lat.
	24 hours, pole and equator
Four satellite coverage	~ 5 hours., CONUS
Average GDOP at W S M R	4 segmented

FIGURE 8 — TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= GAMMA-2B
SATELLITE VIEW PERIODS AT VTS
ELEVATION ANGLE GREATER THAN: 5 DEG

```
                          TIME AFTER EPOCH (HOURS)

STAT  SAT     0   2   4   6   8   10  12  14  16  18  20  22  24
              : . : . : . : . : . : . : . : . : . : . : . : . :
VTS     1     :                      ================
VTS     4     :=           =============                    ===
VTS     7     :      ========                     ===========
VTS    10     :   ===========        =========
VTS    13     :======                                ==========
VTS    16     :              ===           =============
VTS    19     :=========                     ===           ====
VTS    22     :                   ===========        =========
VTS    25     :      ================
              : . : . : . : . : . : . : . : . : . : . : . : . :
```

TABLE OF VIEW PERIODS (HOURS AFTER EPOCH)

STAT	SAT	RISE	SET	RISE	SET	RISE	SET	TOT IN	TOT OUT	MAX OUT SEGMENT
VTS	1	11.65	19.17	.00	.00	.00	.00	7.52	16.48	16.483
VTS	4	.00	.68	6.62	12.72	23.23	24.00	7.55	16.45	10.517
VTS	7	3.73	7.25	18.20	23.15	.00	.00	8.47	15.53	10.950
VTS	10	2.18	7.17	11.72	15.27	.00	.00	8.53	15.47	10.917
VTS	13	.00	3.15	19.67	24.00	.00	.00	7.48	16.52	16.517
VTS	16	7.38	8.67	14.62	20.72	.00	.00	7.38	16.62	10.667
VTS	19	.00	4.70	15.40	16.63	22.62	24.00	7.32	16.68	10.700
VTS	22	10.18	15.17	19.70	23.27	.00	.00	8.55	15.45	10.917
VTS	25	3.63	11.15	.00	.00	.00	.00	7.52	16.48	16.483

FIGURE 9 TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= GAMMA-2B
SATELLITE VIEW PERIODS AT KOD
ELEVATION ANGLE GREATER THAN: 5 DEG

```
                        TIME AFTER EPOCH (HOURS)

STAT  SAT     0     2     4     6     8     10    12    14    16    18    20    22    24
              :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :
KOD    1      :     ========                     ===================
KOD    4      :======               :================                          ========
KOD    7      :             ===========                         ===================
KOD   10      : ===================                 ===========
KOD   13      :======                  ,   ==========                   ===============
KOD   16      :                ==============               ================
KOD   19      :==============                          ============ :               ===
KOD   22      :                         ===================                 ===========
KOD   25      :         =====================                      ==========
              :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :  .  :
```

TABLE OF VIEW PERIODS (HOURS AFTER EPOCH)

STAT	SAT	RISE	SET	RISE	SET	RISE	SET	TOT IN	TOT OUT	MAX OUT SEGMENT
KOD	1	1.97	4.52	11.63	17.82	.00	.00	8.73	15.27	8.150
KOD	4	.00	1.92	7.68	12.50	21.83	24.00	8.90	15.10	9.333
KOD	7	4.88	7.97	16.82	22.52	.00	.00	8.78	15.22	8.850
KOD	10	.80	6.52	12.88	15.98	.00	.00	8.82	15.18	8.317
KOD	13	.00	1.80	9.97	12.50	19.63	24.00	9.70	15.30	8.167
KOD	16	5.82	9.90	15.68	20.50	.00	.00	8.90	15.10	9.317
KOD	19	.00	4.50	13.83	17.90	23.68	24.00	8.88	15.12	9.333
KOD	22	8.80	14.52	20.87	23.97	.00	.00	8.82	15.18	8.333
KOD	25	3.62	9.82	17.97	20.50	.00	.00	8.73	15.27	8.150

FIGURE 10 : TIME-IN-VIEW BARGRAPHS

```
                  TIME AFTER EPOCH (HOURS)

STAT  SAT   0   2   4   6   8   10  12  14  16  18  20  22  24
            : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   1     :  =====                  =============
LOR   1     :========                  ============
SPO   1     :   ====               ==============
MIN   1     : ======                  ==============
MUG   1     :                     ================
VIR   1     :======                    ============
RIC   1     : ===                       =============
YUM   1     :                      ================
SAM   1     :=
BOS   1     :=======                   ============
GUM   1     :     =========    ===========
HOL   1     :                       ===============
HUL   1     :                  =================
IOS   1     :=================                         =====
KOD   1     :   ======            ==============
POG   1     :=========               ===========
VTS   1     :                     ================
            : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   4     :             ==============
LOR   4     :             ===============
SPO   4     :==          =============                  ====
MIN   4     :            ================                ==
MUG   4     :=          =============                     ==
VIR   4     :            ================
RIC   4     :           ==================
YUM   4     :           ==============
SAM   4     :=
BOS   4     :             ===============
GUM   4     :=========                                 =====
HOL   4     :           ===============
HUL   4     :======     ==========                       ===
IOS   4     :                               =============
KOD   4     :====         ===========                  =====
POG   4     :==             ===========              =======
VTS   4     :=          =============                    ===
            : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   7     :    ===========                    =========
LOR   7     :    ============                   ======
SPO   7     :      =========                   ==========
MIN   7     :     ==========                    ========
MUG   7     :     ========                     ===========
VIR   7     :    ============                    ======
RIC   7     :   ===========                       ======
YUM   7     :     =========                     ==========
SAM   7     :=
BOS   7     :    ============                   =======
GUM   7     :                          ==================
HOL   7     :    ==========                     ==========
HUL   7     :                                 ==============
IOS   7     :             ====================
KOD   7     :        =======                 ============
POG   7     :      ===========               ==========
VTS   7     :     ========                     ===========
            : . : . : . : . : . : . : . : . : . : . : . : . :
```

FIGURE 10 (Pg 2 of ?)

TIME AFTER EPOCH (HOURS)

FIGURE 10 (Pg 3 of 3)

TIME AFTER EPOCH (HOURS)

```
STAT  SAT    0   2   4   6   8   10  12  14  16  18  20  22  24
             : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   19     :============                                ====
LOR   19     :=============                                ===
SPO   19     :==========                 =======          ====
MIN   19     :=============               ===             ====
MUG   19     :=========                    ====          =====
VIR   19     :=============                                ===
RIC   19     :==============                             =====
YUM   19     :==========                                 =====
SAM   19     :=
BOS   19     :=============                                ===
GUM   19     :                          ===============
HOL   19     :===========                                =====
HUL   19     :======                      ==========     =====
IOS   19     :               ==============
KOD   19     :=========                 ==========         ===
POG   19     :===========             ==========
VTS   19     :=========                    ====          =====
             : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   22     :                   ==========       ============
LOR   22     :=                  ========         ============
SPO   22     :                  ===========         ==========
MIN   22     :=                  =========         ===========
MUG   22     :                  ============       =========
VIR   22     :=                   =======         ============
RIC   22     :                     =======       ============
YUM   22     :                   ===========       ==========
SAM   22     :=
BOS   22     :=                  ========         ============
GUM   22     :          ===================
HOL   22     :                   ===========      ===========
HUL   22     :                 ===============
IOS   22     :==================                           ===
KOD   22     :                =============           ========
POG   22     :==              ===========           ==========
VTS   22     :                  ============       ==========
             : . : . : . : . : . : . : . : . : . : . : . : . :
SAC   25     :         =============            ====
LOR   25     :          ============         ========
SPO   25     :       ==============               ===
MIN   25     :         ==============          ======
MUG   25     :      ================
VIR   25     :          ============          ======
RIC   25     :           =============         ====
YUM   25     :       ================
SAM   25     :=
BOS   25     :          ============          =======
GUM   25     :   ===========                        =========
HOL   25     :        ===============
HUL   25     :   =================
IOS   25     :=                          =====================
KOD   25     :      ==============               ======
POG   25     :         ===========            =========
VTS   25     :      ================
             : . : . : . : . : . : . : . : . : . : . : . : . :
```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Phase III Baseline

The orbital characteristics of the selected Phase III baseline configuration, OMEGA, is shown in Table 4. This 3 x 8 configuration provides continuous world wide 4 satellite coverage. Time-in-view bargraphs for two candidate upload stations are given in Figures 11 and 12.

Detailed time-in-view data for all locations and all baseline orbit configurations is contained in the following document:

"Time-In-View Bargraphs for Baseline Orbits"
Philco-Ford Tech Memo GPS-TM-005
28 January 1974

TABLE 4

PHASE III - BASELINE CONFIGURATION

SATELLITE NUMBER	ECCENTRIC ANOMALY	LONG OF ASCENDING NODE	MANEUVER FUEL LB. (1 mo.)
3	0	0	10^+
10	45	0	-
11	90	0	-
4	135	0	11^+
12	180	0	-
5	225	0	7^+
13	270	0	-
14	315	0	-
6	0	120	2^+
15	45	120	-
16	90	120	-
1	135	120	8^+
17	180	120	-
2	225	120	5^+
18	270	120	-
19	315	120	-
7	0	240	6^+
20	45	240	-
21	90	240	-
8	135	240	4^+
22	180	240	-
9	225	240	3^+
23	270	240	-
24	315	240	-

FIGURE 11 — TIME-IN-VIEW BARGRAPHS

SATELLITE VIEW PERIODS AT VTS
ELEVATION ANGLE GREATER THAN: 5 DEG

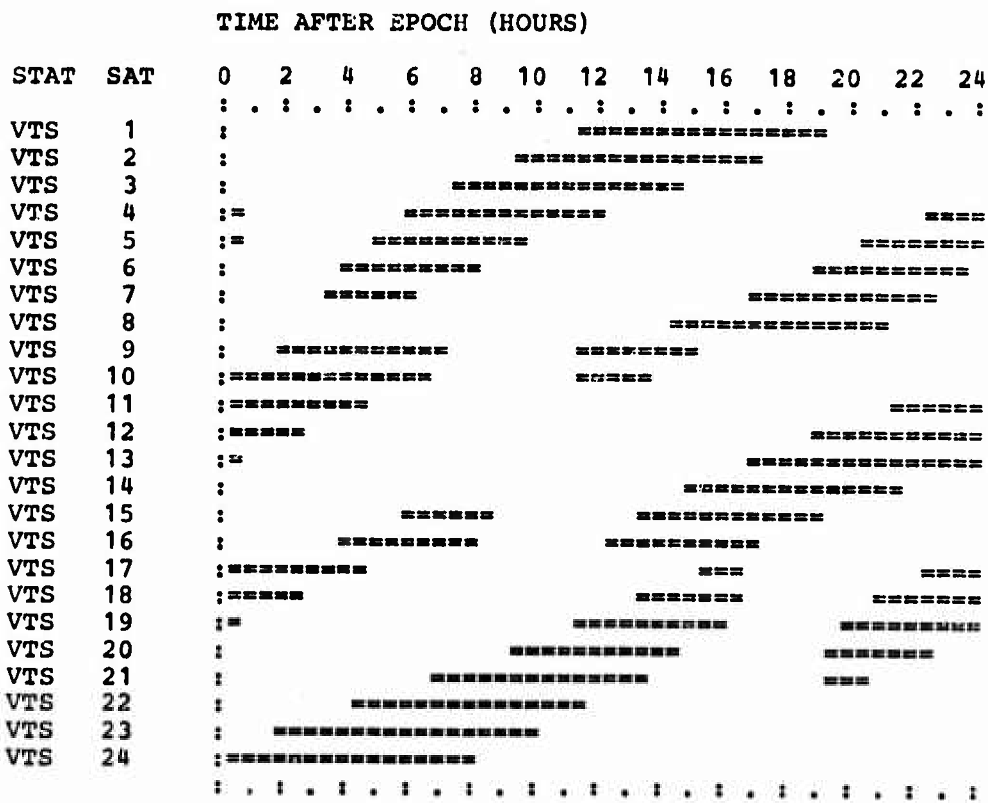
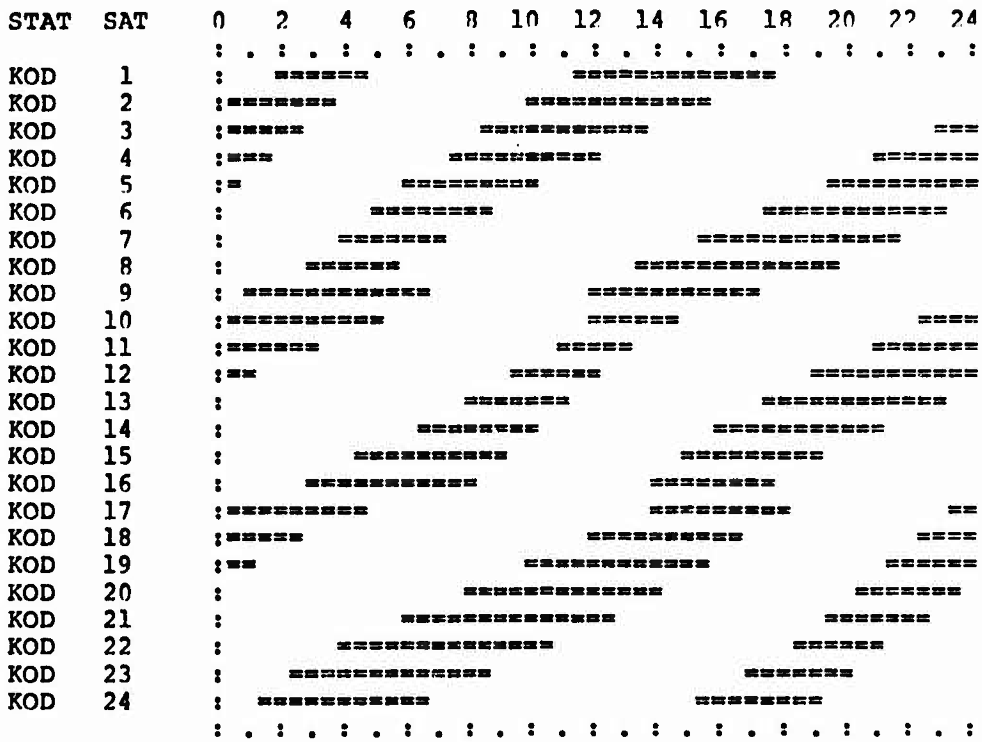


FIGURE 12 TIME-IN-VIEW BARGRAPHS

ORBIT CONFIGURATION= OMEGA
SATELLITE VIEW PERIODS AT KOD
ELEVATION ANGLE GREATER THAN: 5 DEG

TIME AFTER EPOCH (HOURS)



1.2 Mission Requirements

Orbital configurations for GPS are selected to minimize the position determination error an error and be compatible with ground equipment, launch, and satellite design. Constraints applying to all phases of GPS are listed below:

- 120° satellite plane separation
- 63° inclination
- 12 hour earth synchronous orbit, 14341.52 nm semimajor axis
- VAFB Launch
- Minimum stationkeeping - no plane changes
- Useful coverage based on greater than 5 deg. elevation angle mask

1.2.1 Phase I - Special Requirements

Phase I is a four satellite test system designed to demonstrate optimum performance capabilities. Orbits are selected to give:

- At least 2 hours of continuous per day test time over WSMR
- GDOP less than 10 during test time
- 10 minutes upload time per satellite immediately prior to test time
- High elevation angles
- 2 x 2 orbital configurations

1.2.2 Phase II-A - Special Requirements

- 3 x 3 orbit configuration
- 8 hours of continuous test time at WSMR
- GDOP less than 10

1.2.3 Phase II-B Requirements

- Global 2 satellite coverage
- Minimize orbit maneuvers
- 3 x 3 Orbit Configuration

1.2.4 Phase III Requirements

- 3 x 8 configuration
- Global 4 satellite coverage

2.0 PHASE I STUDIES

This section outlines the program developed for the generation and selection of the GPS Phase I baseline orbit configuration suggested in Part I.

2.1 Study Approach

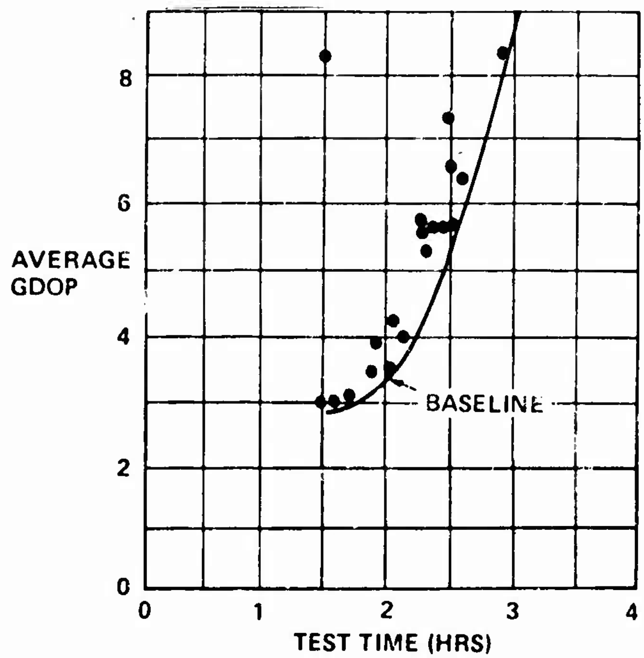
The candidate orbital parameters were analyzed with a timeshare program which calculates viewtime, test time and average GDOP from WSMR for a 24 hour period. Small parameter perturbations were introduced which gave rise to more candidates which were again computer analyzed. In all, approximately 100 orbital configurations were examined.

The GDOP and test time performance figures were plotted on a graph (Figure 13) and a best configuration boundary was defined as the subset of all orbital configurations which gave the lowest GDOP and largest test time combinations. Of these, six representative candidates were chosen for further processing.

A detailed history of GDOP versus time at WSMR was generated. Candidates with GDOP spikes were eliminated. Three candidates remained. Visibility from perspective upload stations was calculated but no candidates could be eliminated on this basis. Elevation angle effects were estimated for the three remaining candidates and stationkeeping requirements were estimated. The result gave a clear advantage to configuration SIGMA. In Section 1.1, the original SIGMA configuration was translated into the equivalent configuration with ascending nodes at 0 and 120 degrees.

Figure 13 BEST CONFIGURATION BOUNDARY

(Solid Curve)



2.2 Generation of Orbit Candidates

Figures 14 through 18 show satellite ground tracks for candidate orbits THETA (2), SIGMA (2½), ZETA (3), and (4) and (5). The dots indicate a typical instantaneous position. The shaded region represents the region of visibility from WSMR. Rough azimuth and elevation information could be gained by optical examination.

Figures 17 and 18 show typical long 5 hour view time configurations which unfortunately give bad GDOP spikes when the satellites reach orbit crossing points. By separating the satellite orbits, excellent GDOP histories can be achieved, however, not without sacrificing time in view and high elevation angles. Figure 19 shows GDOP versus time for the candidate configurations.

2.3 GDOP - Test Time Selection at WSMR

View time, test time, minimum GDOP and average GDOP were calculated for all configurations at the WSMR test site. Since, for some orbit configurations, there is an infinite discontinuity "spike" in the GDOP versus time curve, care must be taken in defining the "average" GDOP. In order to make a definition which is good for all configurations, and which does not go to infinity, we have defined the "average" GDOP to be the average over time of all values of GDOP less than some cut-off value G_o. In the same manner, we have defined "Test-time" as that portion of the viewtime when the orbit configuration produces values of GDOP less than G_o. For this analysis, we have arbitrarily chosen G_o to be equal to 10, and have used a 5 minute sampling interval over our viewtimes.

Figure 20 presents a plot of average GDOP versus test time in an initial attempt to analyze this relationship. In general, it appears that orbit configurations with desirable average GDOP's have short test times. It is speculated that a smooth "best-configuration boundary" may exist for a given type of configuration (eg, 2 x 2). If this is the case, a systematic variation of orbit parameters will locate the boundary. At this point, a specified test time duration can be uniquely associated with an optimized GDOP average.

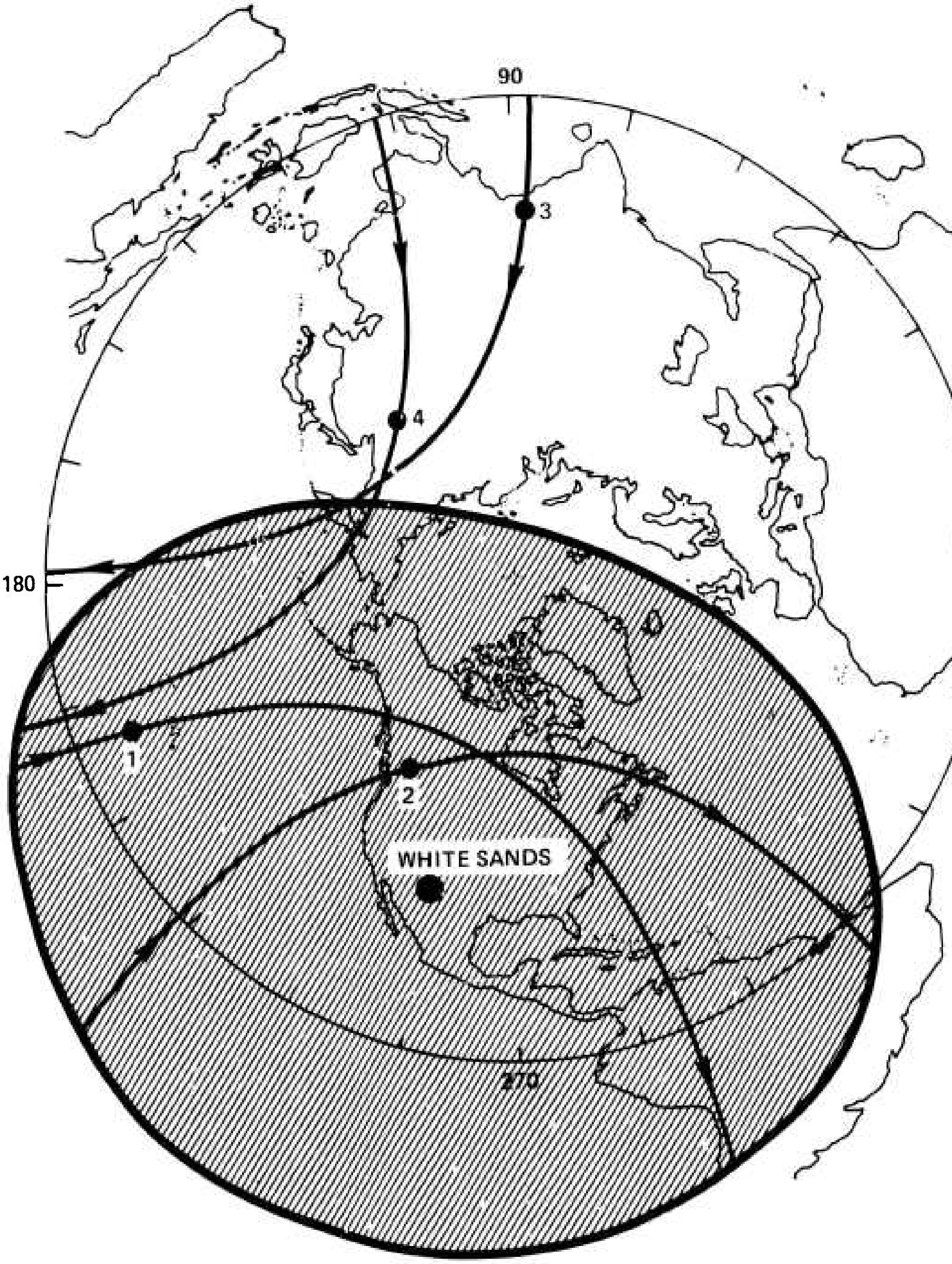


FIGURE 14 Satellite Ground Track
For THETA Configuration

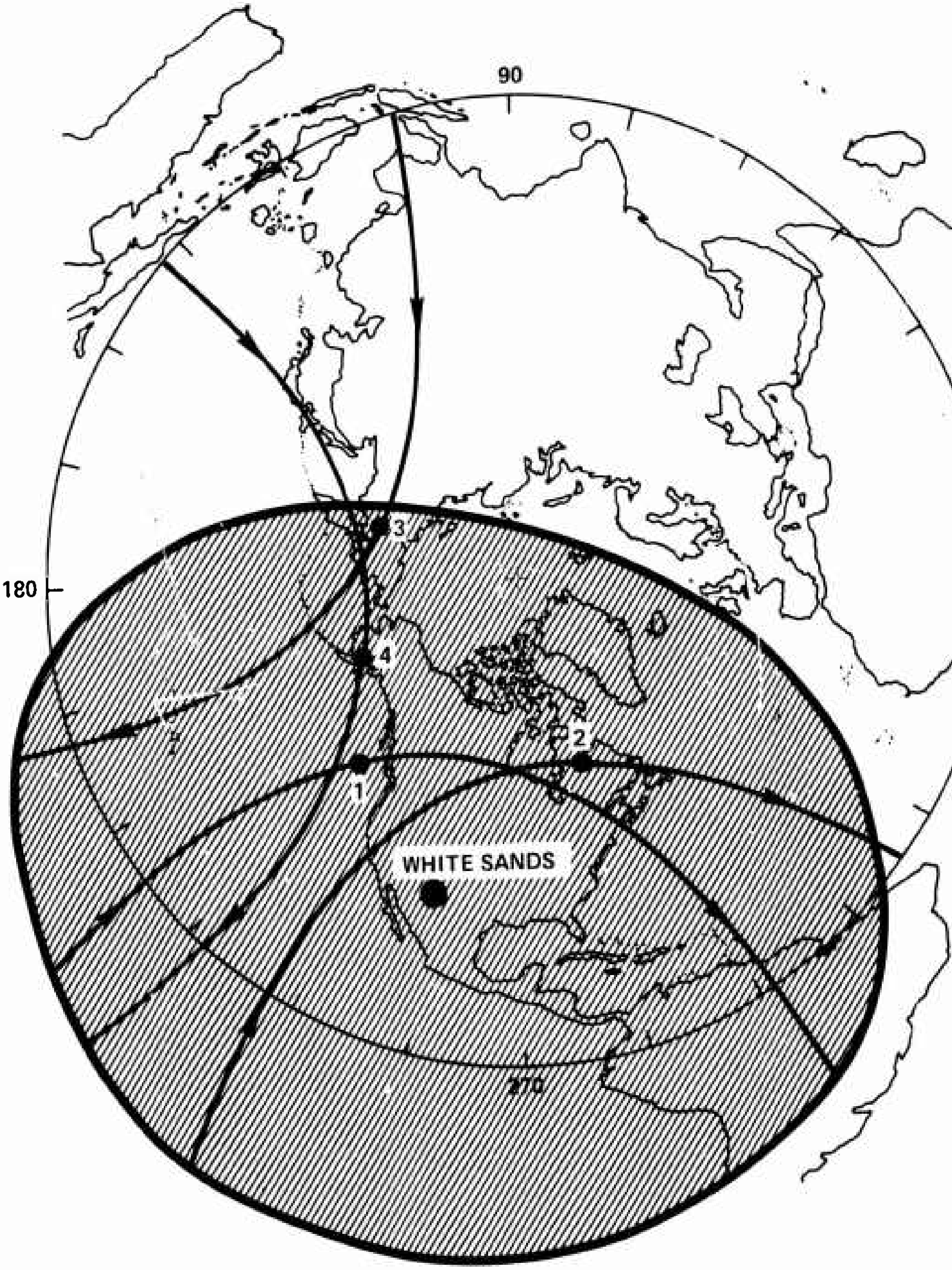


FIGURE 15 Satellite Ground Track
For SIGMA Configuration

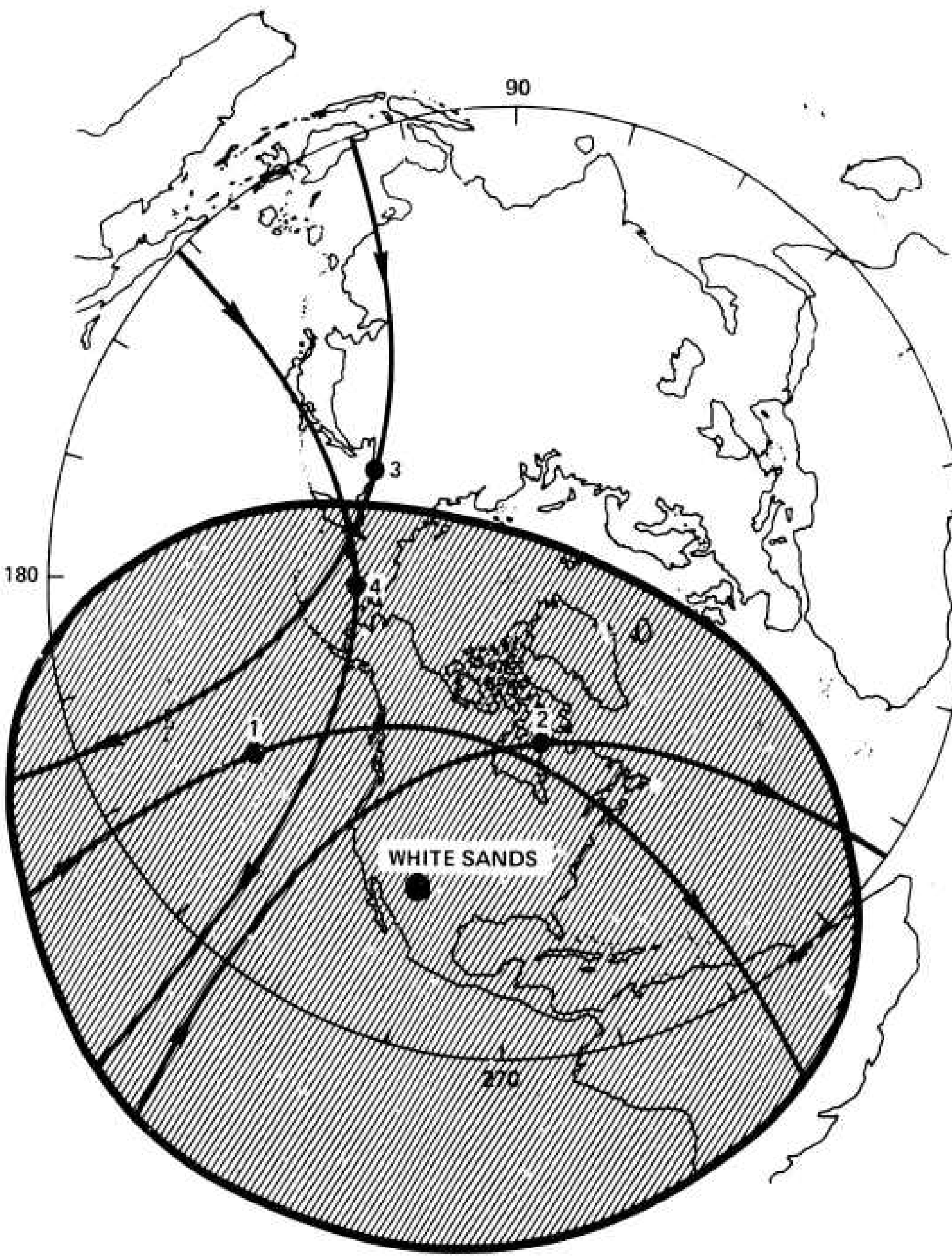


FIGURE 16 Satellite Ground Track For ZETA Configuration

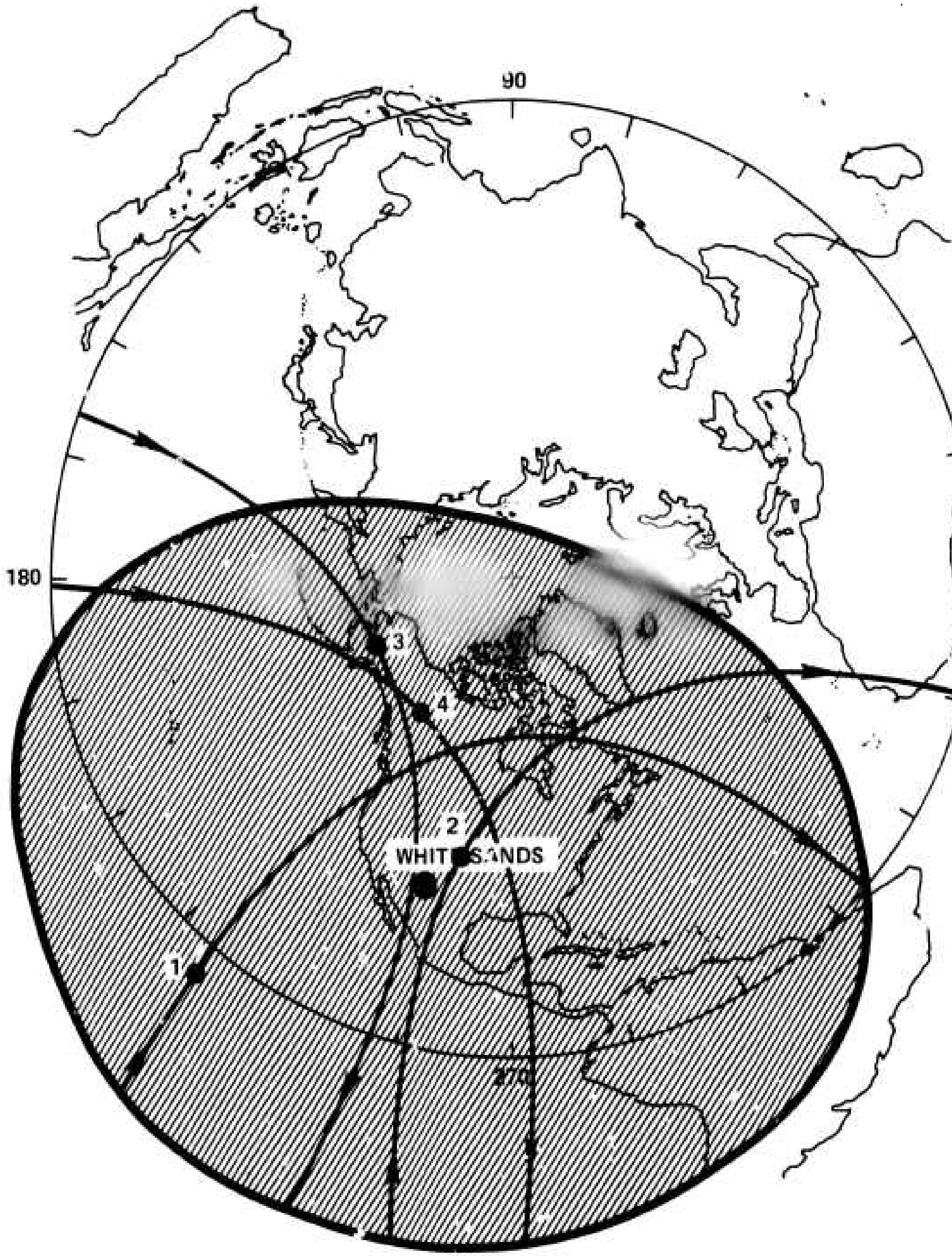


FIGURE 17 Satellite Ground Track
For EPSILON (4) Configuration

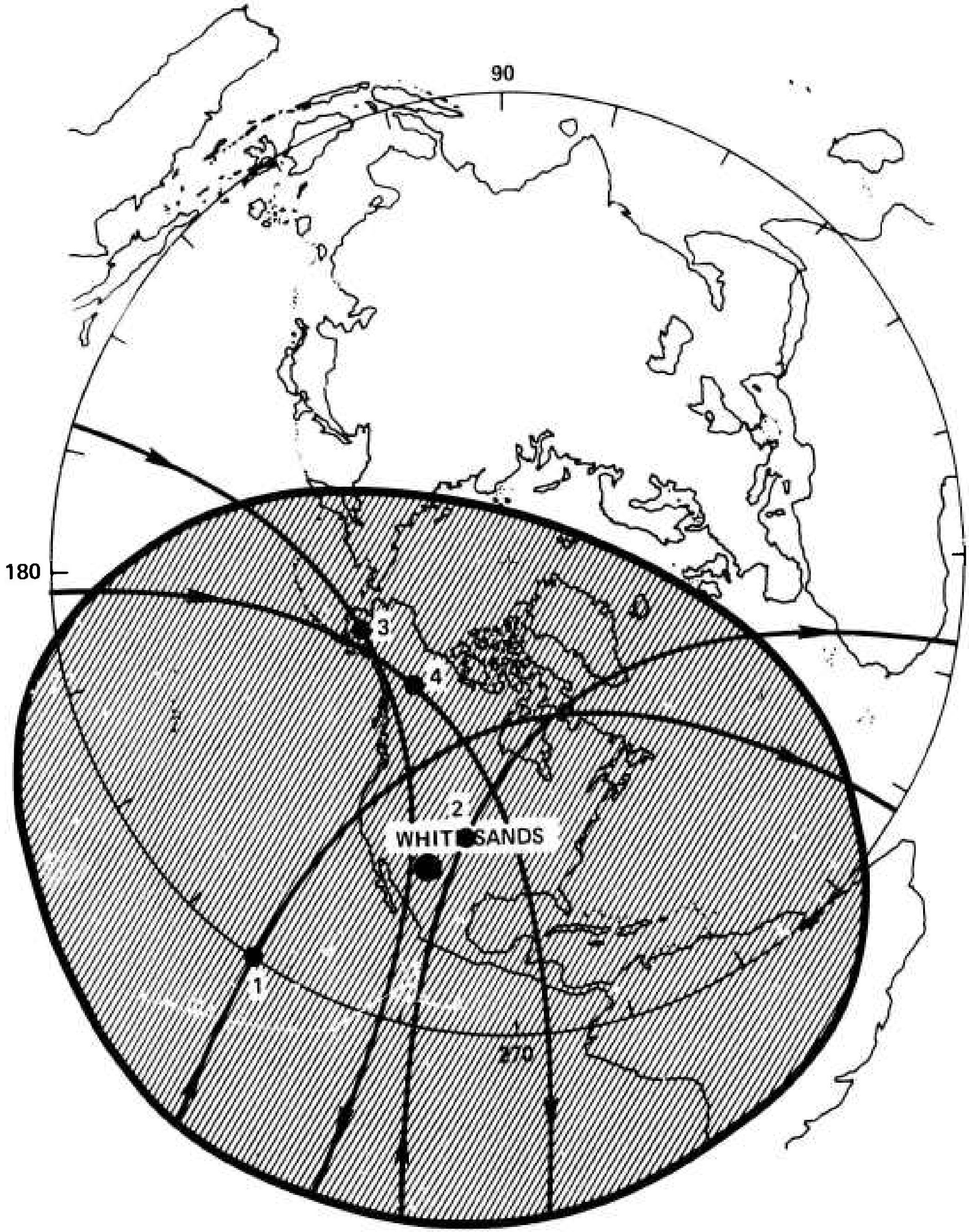


FIGURE 18 Satellite Ground Track For DELTA (5) Configuration

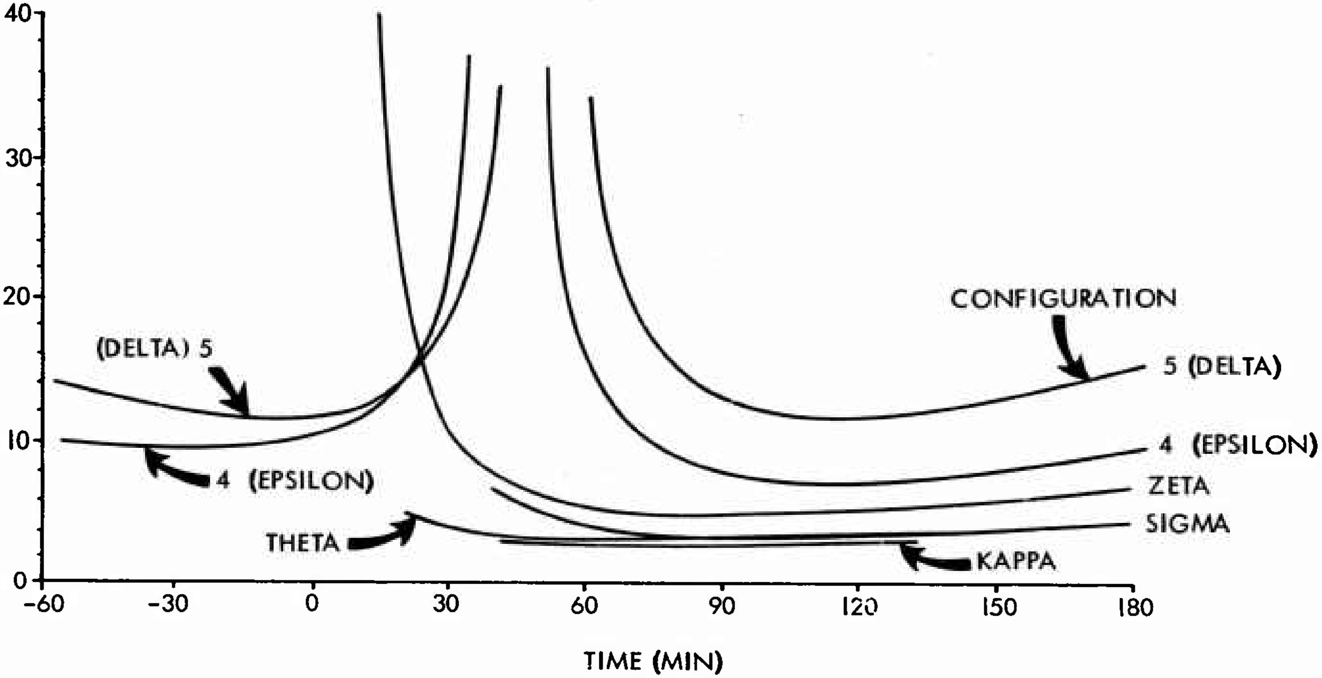


Figure 19 GDOP History Over WSMR
(Phase 1)

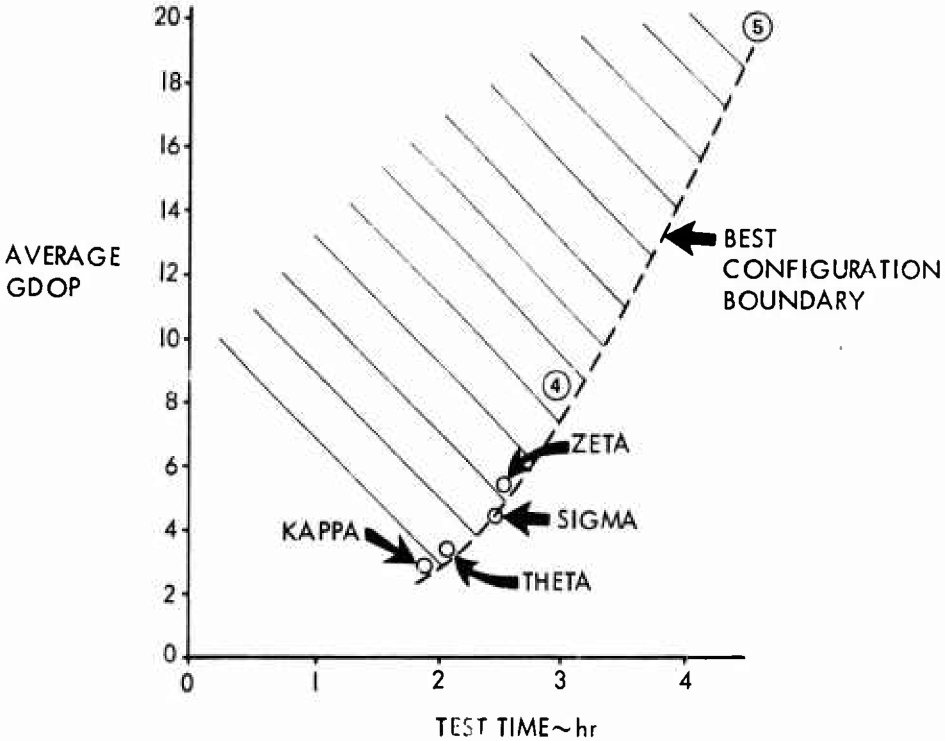


FIGURE 20 - Average GDOP vs Time

CONFIGURATION CANDIDATE	VIEW TIME (MIN)	TEST TIME (MIN)	MINIMUM GDOP	AVERAGE GDOP
1 (KAPPA)	95	95	2.9	3.0
2 (THETA)	125	125	3.2	3.5
3 (ZETA)	165	145	4.9	5.6
4 (EPSILON)	250	175	7.0	8.35
5 (DELTA)	275	-	11.2	-
6 (SIGMA)	145	145	3.8	4.16

TABLE 5 Orbit Configuration Performance

Six candidate orbit configurations which lie on our best configuration boundary, were chosen, named, and further analyzed. Their pertinent performance parameters are listed in Table 5, and their orbit parameters are listed in Table 6.

The entire GDOP history over WSMR was calculated for each of the above named configurations and plotted in Figure 19. We looked for low flat GDOP histories (without spikes) and test times over two hours. Configurations ZETA, SIGMA, and THETA satisfied our criteria. KAPPA, though showing excellent GDOP, was eliminated due to its short 45 minute test time.

2.4 Upload Requirements

To examine the upload problem, a timeshare program originally developed to investigate the ground station loading was implemented. Tables 7 through 9 show the number of satellites visible from a ground station network as a function of time for the ZETA, THETA, and SIGMA configurations.

The first column shows the number of satellites seen from WSMR. Test period begins when all four satellites are in view; for the ZETA-case figure this happens at 30 minutes. Examination of other columns shows that for all three configurations at least one half hour is available from any of the four potential upload locations (KTS, VTS, SPO, ELM), to load the fourth and last satellite. More time is available to load the others. Hence no upload problem exists for any of our three candidates.

		ECCENTRIC ANOMALY IN DEG				LONGITUDE OF ASCENDING NODE IN DEG			
SAT		1	2	3	4	1	2	3	4
CONFIG.	DNSS DESIGNATION								
1	KAPPA	77,	122,	77,	122	165,	165,	45,	45
2	THETA	70,	119,	85,	122	165,	165,	45,	45
3	ZETA	35,	75,	75,	130	195,	195,	75,	75
4	EPSILON	-10,	40,	90,	130	235,	235,	115,	115
5	DELTA	0	40,	90,	130	235,	235,	115,	115
2.5	SIGMA	41	81	64	124	195	195	75	75

TABLE 6 ORBIT PARAMETERS OF CANDIDATE CONFIGURATIONS

GROUND STATIONS

TIME MINUTES	KOL	BHS	IOS	GTS	NTS	HTS	VTS	LOR	SPO	ALP
15.00	3	3	0	1	3	4	4	0	4	4
30.00	3	3	0	1	3	4	4	0	4	4
45.00	4	4	0	1	3	4	4	1	4	4
60.00	4	4	0	1	3	4	4	1	4	4
75.00	4	4	0	1	3	4	4	1	4	4
90.00	4	4	0	1	3	3	4	1	3	4
105.00	4	4	0	1	3	3	3	1	3	3
120.00	4	3	0	1	2	2	3	1	3	3
135.00	4	3	0	1	2	2	3	2	3	2
150.00	4	3	0	1	2	2	3	2	2	2
165.00	4	2	0	1	2	2	3	2	2	2
180.00	4	2	0	1	2	2	2	2	2	2
195.00	2	2	0	1	2	1	2	2	2	2
210.00	2	2	0	1	1	1	2	2	1	2
225.00	2	2	0	1	1	1	2	2	1	1
240.00	2	1	0	1	1	1	1	2	1	0
255.00	2	1	0	1	1	0	1	2	1	0
270.00	1	1	0	1	1	0	0	3	1	0
285.00	1	1	0	1	1	0	0	3	1	0
300.00	1	1	0	0	1	0	0	3	0	0
315.00	1	1	0	0	1	0	0	3	0	0
330.00	0	1	0	0	1	0	0	3	0	0
345.00	0	0	0	0	0	0	0	3	0	0
360.00	0	0	1	0	0	0	0	3	0	0
375.00	0	0	1	0	0	0	0	3	0	0
390.00	0	0	1	0	0	0	0	3	0	0
405.00	0	0	1	0	0	0	0	3	1	0
420.00	0	1	1	0	0	0	0	3	1	0
435.00	0	1	1	0	0	0	0	4	1	0
450.00	0	1	1	0	0	0	0	4	1	0
465.00	1	1	2	0	0	0	0	4	1	0
480.00	1	1	2	0	0	0	0	4	1	1
495.00	1	1	2	0	0	0	0	3	1	1
510.00	1	1	2	0	0	0	1	3	2	1
525.00	2	2	2	0	0	0	1	3	2	1
540.00	2	2	2	0	0	1	2	3	2	1
555.00	2	2	2	0	0	1	2	3	2	2
570.00	2	2	2	0	0	1	2	3	2	2
585.00	2	2	2	0	0	1	2	3	2	2
600.00	2	2	2	0	0	1	2	3	2	2
615.00	2	2	2	0	0	2	1	2	2	2
630.00	2	2	2	0	0	2	1	2	2	2
645.00	2	2	2	0	0	2	1	2	2	2
660.00	1	2	2	0	0	3	1	2	2	1
675.00	1	2	3	1	0	3	1	1	2	2
690.00	1	2	3	1	0	3	1	1	1	2
705.00	1	2	3	1	0	2	1	0	1	2
720.00	1	1	2	1	0	2	1	0	1	2
735.00	1	1	2	1	1	3	2	0	2	2
750.00	1	2	2	1	1	3	2	1	2	2
765.00	1	2	2	1	1	3	2	2	2	3
780.00	1	2	2	1	1	3	1	2	2	3
795.00	1	2	2	2	1	3	1	2	1	2
810.00	0	2	2	2	1	2	1	2	1	2
825.00	0	1	2	2	1	2	0	2	1	2
840.00	0	1	2	2	1	2	0	2	1	1
855.00	0	1	2	2	2	2	0	2	0	1
870.00	0	1	2	2	2	2	0	2	0	0
885.00	0	0	2	2	2	2	0	2	0	0
900.00	0	0	2	2	2	1	0	2	0	0
915.00	0	0	2	2	2	1	0	2	0	0
930.00	0	0	2	2	2	1	0	1	0	0
945.00	0	0	2	2	2	0	0	1	0	0
960.00	0	0	2	2	2	0	0	1	0	0
975.00	0	0	2	2	0	0	0	1	0	0
990.00	0	0	2	2	0	0	0	1	0	0
1005.00	0	0	2	2	0	0	0	1	0	0
1020.00	0	0	3	2	0	0	0	1	0	0
1035.00	0	0	2	2	0	0	0	1	0	0
1050.00	0	0	1	2	0	0	0	1	0	0
1065.00	0	0	1	2	0	0	0	1	0	0
1080.00	0	0	1	2	0	0	0	1	0	0
1095.00	0	0	1	2	0	0	0	0	0	0
1110.00	0	0	1	2	0	0	0	0	0	0
1125.00	0	0	1	2	0	0	0	0	0	0
1140.00	0	0	1	1	1	0	0	0	0	0
1155.00	0	0	1	1	1	0	0	0	0	0
1170.00	0	0	1	1	2	0	1	0	0	0
1185.00	0	0	1	2	2	0	1	0	0	0
1200.00	1	0	1	2	2	1	1	0	0	1
1215.00	1	0	1	2	2	1	1	0	0	1
1230.00	1	0	1	2	3	1	1	0	1	2
1245.00	1	0	1	2	3	2	1	0	1	2
1260.00	1	1	1	2	3	2	3	0	1	2
1275.00	1	1	1	2	3	2	3	0	1	3
1290.00	1	1	1	2	3	2	3	0	1	3
1305.00	2	1	1	2	3	2	3	0	2	3
1320.00	2	1	1	2	3	3	3	0	2	3
1335.00	3	2	1	2	3	3	3	0	2	3
1350.00	3	2	1	2	3	4	3	0	3	3
1365.00	3	2	1	2	3	4	3	0	3	3
1380.00	3	3	1	3	3	4	3	0	3	3
1395.00	3	3	1	3	3	4	3	0	3	4
1410.00	3	3	0	3	4	4	3	0	3	4
1425.00	3	3	0	2	4	4	4	0	3	4
1440.00	3	3	0	2	4	4	4	0	4	4

TABLE 7 NUMBER OF VISIBLE SATELLITES
(SIGMA CONFIGURATION)

TIME MINUTES	GROUND STATIONS HOB	HHB	IOB	GTB	HTS	ETT	VTT	LOF	SPD	ALM
15.00	4	4	0	2	4	4	4	0	4	4
30.00	4	4	0	2	3	4	4	0	4	4
45.00	4	4	0	1	3	4	4	0	4	4
60.00	4	4	0	1	3	4	4	1	4	4
75.00	4	4	0	1	3	4	4	1	4	4
90.00	4	4	0	1	3	4	4	1	3	4
105.00	4	4	0	1	3	2	4	1	3	4
120.00	4	3	0	1	3	2	3	1	3	2
135.00	4	3	0	1	2	2	3	1	3	2
150.00	4	3	0	1	2	2	3	2	2	2
165.00	4	2	0	1	2	2	2	2	2	2
180.00	3	2	0	1	2	2	2	2	2	2
195.00	3	2	0	1	1	2	2	2	2	2
210.00	2	2	0	1	1	1	2	2	2	2
225.00	2	2	0	1	1	0	2	2	1	1
240.00	2	2	0	1	1	0	2	2	1	0
255.00	1	1	0	1	1	0	1	3	1	0
270.00	1	1	0	0	1	0	0	3	1	0
285.00	1	1	0	0	1	0	0	3	1	0
300.00	1	1	0	0	1	0	0	3	1	0
315.00	1	1	0	0	0	0	0	3	0	0
330.00	1	1	0	0	0	0	0	3	0	0
345.00	0	0	0	0	0	0	0	3	0	0
360.00	0	0	0	0	0	0	0	3	0	0
375.00	0	0	1	0	0	0	0	3	0	0
390.00	0	0	1	0	0	0	0	3	1	0
405.00	0	0	1	0	0	0	0	4	1	0
420.00	0	1	1	0	0	0	0	4	1	0
435.00	0	1	1	0	0	0	0	4	1	0
450.00	0	1	1	0	0	0	0	4	1	0
465.00	1	1	1	0	0	0	0	4	1	0
480.00	1	1	2	0	0	0	0	4	2	1
495.00	1	1	2	0	0	0	0	4	2	1
510.00	2	2	2	0	0	0	1	4	2	1
525.00	2	2	2	0	0	0	2	4	2	1
540.00	2	2	2	0	0	1	2	4	2	2
555.00	2	2	2	0	0	1	2	4	2	2
570.00	2	2	2	0	0	1	2	3	2	2
585.00	2	2	2	0	0	1	2	3	2	2
600.00	2	2	2	0	0	2	1	2	2	2
615.00	2	2	2	0	0	2	1	2	2	2
630.00	2	2	2	0	0	2	1	2	2	2
645.00	1	2	2	0	0	2	1	2	2	1
660.00	1	2	3	0	0	3	1	2	2	1
675.00	1	2	3	0	0	3	1	1	1	1
690.00	1	2	3	1	0	2	1	1	1	2
705.00	1	1	3	1	0	2	1	1	1	2
720.00	1	1	3	1	0	2	1	1	1	2
735.00	1	1	2	1	0	2	1	0	2	2
750.00	1	2	2	1	1	3	0	1	2	2
765.00	1	2	2	1	1	3	1	2	2	1
780.00	1	2	2	1	1	3	1	2	2	2
795.00	0	2	3	1	1	2	1	2	2	2
810.00	0	2	3	2	1	2	1	2	1	2
825.00	0	2	3	2	1	2	0	2	0	2
840.00	0	1	2	2	1	2	0	2	0	1
855.00	0	0	2	2	1	2	0	2	0	1
870.00	0	0	2	2	2	2	0	2	0	0
885.00	0	0	2	2	2	2	0	2	0	0
900.00	0	0	2	2	2	1	0	1	0	0
915.00	0	0	2	2	2	1	0	1	0	0
930.00	0	0	2	2	2	1	0	1	0	0
945.00	0	0	2	2	2	1	0	1	0	0
960.00	0	0	2	2	2	0	0	1	0	0
975.00	0	0	3	2	0	0	0	1	0	0
990.00	0	0	3	2	0	0	0	1	0	0
1005.00	0	0	3	2	0	0	0	1	0	0
1020.00	0	0	2	2	0	0	0	1	0	0
1035.00	0	0	2	3	0	0	0	1	0	0
1050.00	0	0	2	3	0	0	0	1	0	0
1065.00	0	0	2	2	0	0	0	0	0	0
1080.00	0	0	2	2	0	0	0	0	0	0
1095.00	0	0	1	2	0	0	0	0	0	0
1110.00	0	0	1	2	1	0	0	0	0	0
1125.00	0	0	1	2	1	0	0	0	0	0
1140.00	0	0	1	1	1	0	0	0	0	0
1155.00	0	0	1	1	1	0	0	0	0	0
1170.00	0	0	1	2	2	1	0	0	0	0
1185.00	0	0	1	2	2	1	1	0	0	0
1200.00	0	0	1	2	2	1	1	0	0	1
1215.00	1	0	1	2	2	1	1	0	0	2
1230.00	1	0	1	2	2	1	1	0	0	2
1245.00	1	0	1	2	3	1	2	0	1	2
1260.00	1	0	1	2	3	2	2	0	1	2
1275.00	1	1	1	2	3	2	3	0	1	2
1290.00	1	1	1	2	3	2	3	0	2	3
1305.00	2	1	1	2	3	2	3	0	2	3
1320.00	3	2	1	2	3	4	3	0	2	3
1335.00	3	2	1	2	3	4	3	0	2	3
1350.00	3	2	1	2	3	4	3	0	2	3
1365.00	3	2	1	3	4	4	3	0	3	4
1380.00	3	2	0	3	4	4	3	0	3	4
1395.00	3	3	0	2	4	4	3	0	3	4
1410.00	3	3	0	2	4	4	4	0	3	4
1425.00	3	3	0	2	4	4	4	0	4	4
1440.00	3	3	0	2	4	4	4	0	4	4

TABLE 8 NUMBER OF VISIBLE SATELLITES
(THETA CONFIGURATION)

GROUND STATIONS

TIME MINUTES	GOL	HHS	IOL	CTS	ATS	ETS	VTS	LOR	EPO	ALP
15.00	3	4	0	2	3	4	4	1	4	4
30.00	4	4	0	2	3	3	4	1	3	4
45.00	4	4	0	2	3	3	4	1	3	4
60.00	4	3	0	2	3	3	3	1	2	3
75.00	4	2	0	2	3	3	3	1	2	3
90.00	4	2	0	2	2	3	3	1	2	3
105.00	4	2	0	2	2	3	3	2	2	3
120.00	4	2	0	2	2	3	3	2	2	2
135.00	4	2	0	2	2	2	3	2	2	2
150.00	2	2	0	2	2	2	3	2	1	2
165.00	1	2	0	2	2	1	2	3	1	1
180.00	1	1	0	2	2	1	2	2	1	1
195.00	1	1	0	1	2	0	1	2	1	0
210.00	1	1	0	1	2	0	1	2	1	0
225.00	1	1	0	1	1	0	0	2	1	0
240.00	1	1	0	1	1	0	0	2	1	0
255.00	1	1	0	1	1	0	0	2	0	0
270.00	1	1	0	1	1	0	0	2	0	0
285.00	1	0	0	1	1	0	0	2	0	0
300.00	0	0	1	0	0	0	0	3	0	0
315.00	0	0	1	0	0	0	0	3	0	0
330.00	0	0	1	0	0	0	0	3	0	0
345.00	0	0	1	0	0	0	0	3	0	0
360.00	0	0	1	0	0	0	0	3	0	0
375.00	0	0	1	0	0	0	0	3	0	0
390.00	0	0	1	0	0	0	0	3	1	0
405.00	1	0	1	0	0	0	0	3	1	0
420.00	1	1	2	0	0	0	1	3	1	0
435.00	1	1	2	0	0	0	1	3	1	1
450.00	1	1	2	0	0	0	1	3	1	1
465.00	2	1	2	0	0	0	2	3	2	1
480.00	2	1	2	0	0	0	2	3	2	2
495.00	2	2	2	0	0	1	2	3	2	2
510.00	2	2	2	0	0	1	2	3	2	2
525.00	2	2	2	0	0	1	2	2	2	2
540.00	2	2	2	0	1	1	2	2	2	2
555.00	2	2	2	0	1	2	2	1	2	2
570.00	2	2	2	0	1	2	2	1	2	2
585.00	2	2	2	0	1	3	2	1	2	2
600.00	2	2	2	0	1	3	2	1	3	3
615.00	2	2	2	0	1	3	2	1	3	3
630.00	2	2	2	1	1	3	2	1	3	3
645.00	2	3	2	1	1	3	2	2	3	3
660.00	2	3	1	1	1	3	1	2	3	3
675.00	2	3	1	1	2	3	1	1	3	2
690.00	2	3	1	1	1	4	1	1	3	2
705.00	1	3	2	1	1	3	1	1	3	3
720.00	1	3	2	1	1	3	1	1	3	3
735.00	1	3	2	1	1	3	1	2	3	2
750.00	1	3	2	2	1	3	0	2	1	2
765.00	1	3	2	2	1	3	0	2	1	1
780.00	1	1	2	2	1	2	0	2	1	0
795.00	1	1	2	2	1	2	0	2	1	0
810.00	0	1	3	2	1	1	0	2	1	0
825.00	0	1	3	2	1	1	0	2	1	0
840.00	0	1	3	2	1	1	0	2	1	0
855.00	0	1	3	2	0	1	0	2	0	0
870.00	0	1	3	2	0	0	0	2	0	0
885.00	0	1	3	2	0	0	0	2	0	0
900.00	0	0	3	2	0	0	0	2	0	0
915.00	0	0	3	2	0	0	0	2	0	0
930.00	0	0	3	2	0	0	0	2	0	0
945.00	0	0	3	2	0	0	0	2	0	0
960.00	0	0	3	2	0	0	0	2	0	0
975.00	0	0	3	1	0	0	1	1	0	0
990.00	0	0	3	1	0	0	0	1	0	0
1005.00	0	0	3	1	0	0	0	1	0	0
1020.00	0	0	3	1	0	0	0	1	0	0
1035.00	0	0	3	1	0	0	0	1	0	0
1050.00	0	0	3	1	0	0	0	1	0	0
1065.00	0	0	2	0	0	0	0	1	0	0
1080.00	0	0	2	1	1	0	0	0	0	0
1095.00	0	0	2	1	1	0	1	0	0	0
1110.00	0	0	2	1	1	0	1	0	0	0
1125.00	0	0	2	1	1	0	1	0	0	1
1140.00	1	0	2	1	1	0	1	0	0	1
1155.00	1	0	2	1	1	1	1	0	0	1
1170.00	1	0	2	1	2	1	1	0	1	1
1185.00	1	0	2	2	2	1	1	0	1	1
1200.00	1	1	2	2	2	1	1	0	1	1
1215.00	1	1	2	3	2	1	2	0	1	1
1230.00	1	1	2	3	2	1	2	0	1	2
1245.00	1	1	2	3	2	2	2	0	1	2
1260.00	2	1	2	3	2	3	2	0	1	2
1275.00	2	1	2	3	2	3	2	0	1	3
1290.00	2	1	2	3	3	3	2	0	1	3
1305.00	2	1	1	3	3	3	2	0	1	3
1320.00	2	1	1	3	3	3	3	0	2	3
1335.00	2	1	1	3	3	4	3	0	3	3
1350.00	2	2	1	3	3	4	3	0	3	3
1365.00	3	3	1	3	3	4	3	0	3	4
1380.00	3	3	1	3	3	4	3	0	3	4
1395.00	3	3	0	3	2	4	3	0	3	4
1410.00	3	3	0	3	3	4	4	1	4	4
1425.00	3	3	0	3	3	4	4	1	4	4
1440.00	3	3	0	2	3	4	4	1	4	4

TABLE 9 NUMBER OF VISIBLE SATELLITES
(ZETA CONFIGURATION)

2.5 Elevation Angle and Stationkeeping Selection

2.5.1 Elevation Angle Error Analysis

It is known that errors in arrival time of satellite signals are in part due to the uncertainty of the speed of light in the troposphere and ionosphere. In the Navigation Satellite Constellation Study[1] user range measurement errors are estimated to be:

	Class a	Class b
Troposphere	$0.4 \text{ Csc } E$	$8 \text{ Csc } E$
Ionosphere	$6.9 \text{ Csc}\sqrt{(10^\circ)^2 + E^2}$	$13.8 \text{ Csc}\sqrt{(10^\circ) + E^2}$

where

E = elevation angle of a given satellite.

The scale coefficient multiplying the Csc E is derived from detailed analysis of user equipment, and atmospheric wave propagation. The geometric contribution is contained entirely in the elevation angle function. We singled out the elevation angle effect by calculating

$$GDOP_E = \frac{U_i}{r_i} \text{ Csc } E_i$$

where U_i is the user's i^{th} coordinate

r_i is the slant range to the j th satellite

E_j is the elevation angle of the jth satellite.

---

[1] Navigation Satellite Constellation Study Final Report, Contract N00-123-68-C-0319, p. 4-7.

$GDOP_E$ is the sum of the squares of the user position error due to a slant range uncertainty of 1 ft•Csc E.

Figure 21 shows a plot of $GDOP_E$ history over WSMR for the three remaining configurations. The expected upswing toward the beginning and end of the test period due to low elevation angle is evident. Configuration SIGMA was chosen as optimum by visual inspection.

Elevation angle probability distributions for 4 selected ground stations are derived in Appendix D for the SIGMA orbit configuration. Appendix D also gives the Phase I elevation angle distribution during the test period at WSMR.

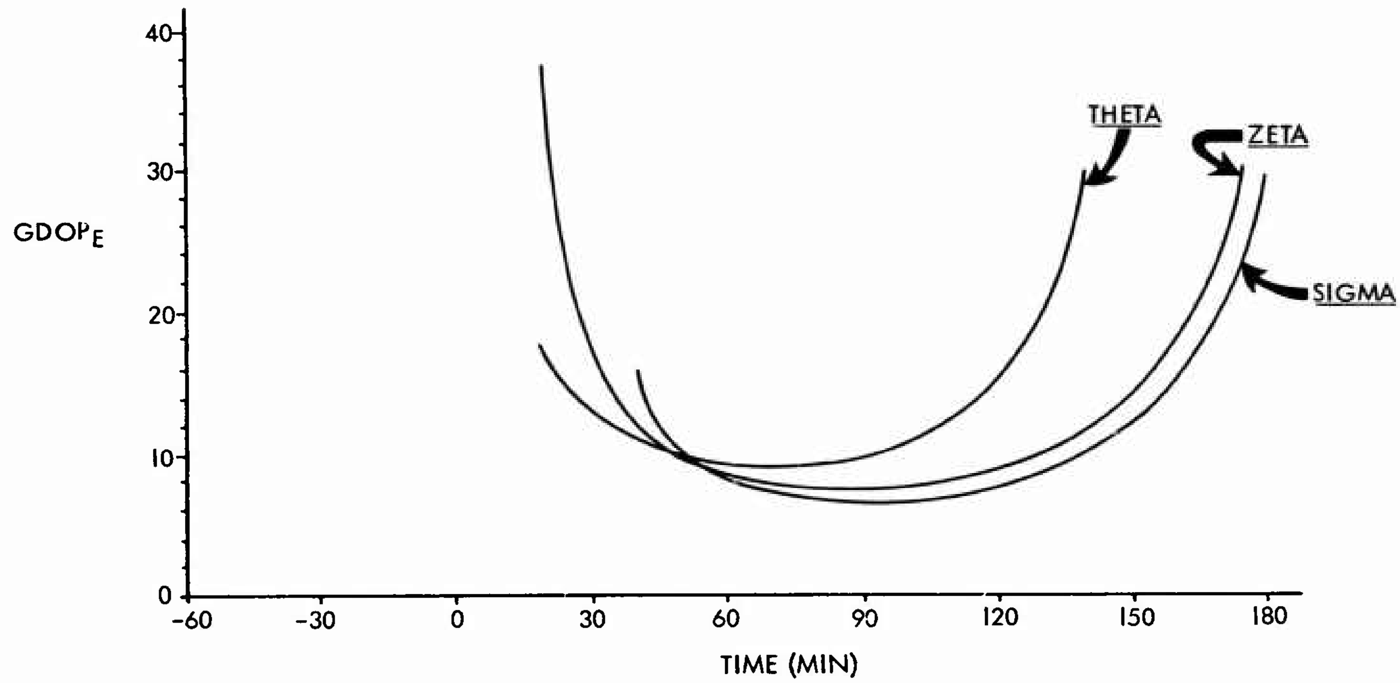


FIGURE 21 Elevation GDOP$_E$ History Over Holloman

2.5.2 Stationkeeping

Fuel costs for stationkeeping are treated in Appendix C. In this section an attempt has been made to answer two questions. First, how large a deviation between nominally assigned station and actual satellite position can be tolerated, second, is there an advantage of one configuration over another.

By calculating performance characteristics of the orbital configurations for small deviations in orbital parameters we were able to conclude that initial errors on the order of $\pm 2^{\circ}$ for inclination, eccentric anomaly and ascending node will not seriously degrade system performance; however, initial errors in the semi major axis will cause the satellites to drift with respect to each other, causing an error in eccentric anomaly increasing linearly with time.

The effect of random eccentric anomaly drift was examined for SIGMA, THETA, and ZETA by changing the anomaly of all satellites by $\pm$ 3, 6, 12 degrees in all possible combinations. This gives 144 configurations evaluated in all. These were plotted on a test time versus average GDOP graph and their boundaries drawn. Figure 22 gives the plot for the THETA configurations.

As expected, performance degenerates with increasing mean anomaly error. To the first approximation the probability of attaining any specific performance is roughly proportional to the area defining that performance. For example, the probability for test time to slip below 1.5 hours is:

0% for a $\pm 3^{\circ}$ error
1% for a $\pm 6^{\circ}$ error
30% for a $\pm 12^{\circ}$ error

Candidate configurations were compared by superimposing $\pm 6^{\circ}$ error bounds. The result is shown in Figure 23. Configuration ZETA shows a tendency toward bad GDOP; configuration THETA toward low test time. Configuration SIGMA has the preferred error bounds. If mean anomaly is allowed to drift to $\pm 6^{\circ}$, configuration SIGMA will degenerate to another configuration with a $\sim$90% probability of GDOP less than five and an 80% probability of test times above 2 hours.

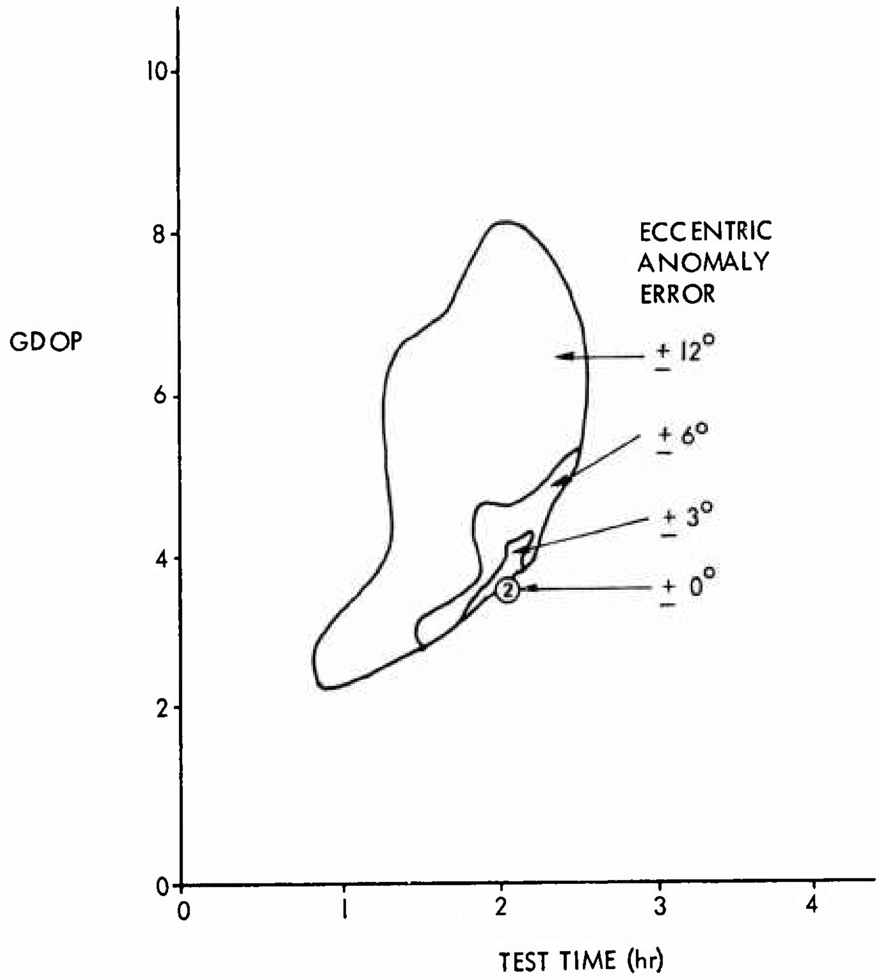


FIGURE 22 Eccentric Anomaly Error Bounds For Theta Configuration

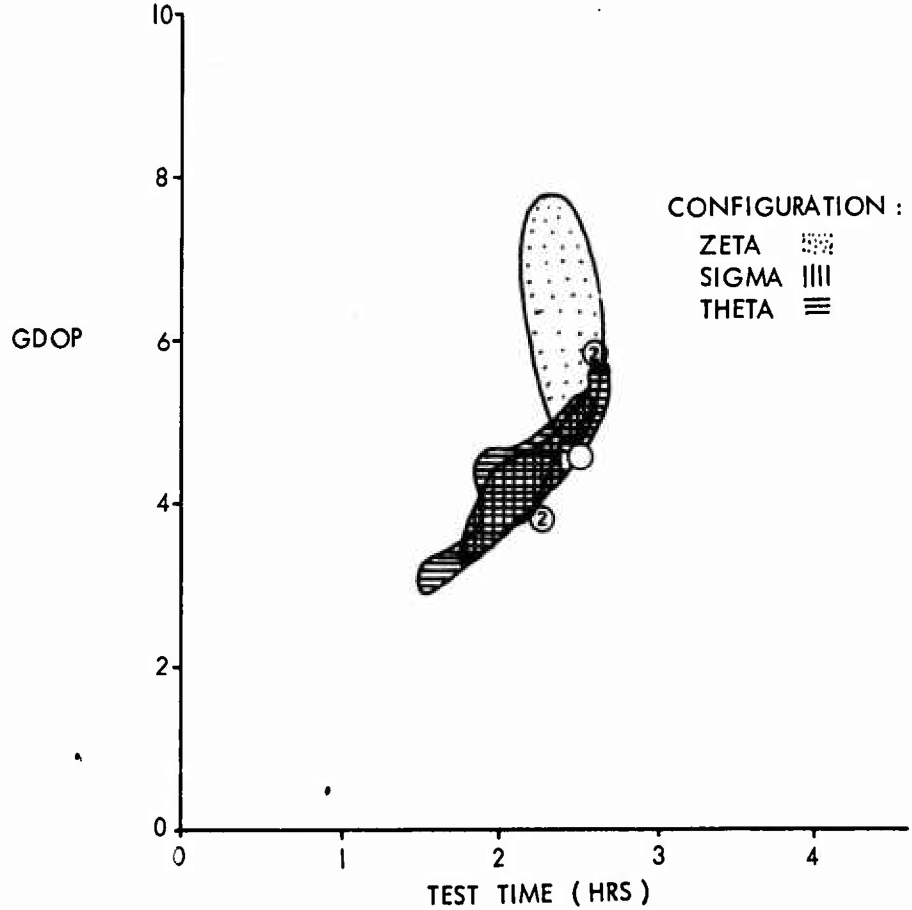


FIGURE 23 $\pm 6^{\circ}$ Eccentric Anomaly Error Bounds For Candidate Orbital Configurations

2.6 Orbit Evaluation Matrix

In an effort to present the results of our Phase I study in an easily comprehensible manner, a matrix presentation allowing comparison of alternative configurations has been generated.

Table 10 shows a list of performance parameters upon which evaluation and final configuration selection has been based. The criteria weight column gives a numerical measure of the relative importance placed upon each of the evaluation criteria.

Each of the numerical performance figures have been converted into evaluation figures of merit by a formula presented in column two, Table 11. The formulas were chosen to compensate for differing units on performance figures while maintaining the relative weights. Comparison and evaluation of alternative configuration was thus reduced to finding the highest evaluation score in Table 11. The highest total score of 63 was recorded for the SIGMA configuration which was thus judged to be the best and recommended as a baseline.

TABLE 10 CHARACTERISTICS OF CANDIDATE ORBITS

SELECTION CRITERIA	CRITERIA WEIGHT	DELTA	EPSILON	ZETA	SIGMA	THETA	KAPPA
TEST TIME (WSMR) (hr)	20	4.2	3.3	2.5	2.4	2.1	1.6
AVE GDOP	20	20	11	6	4.2	3.5	3
MAX GDOP	10	> 50	>50	39	7	5	4
UPLOAD TIME FROM VTS (MIN)	10	30	31	20	19	21	23
ELEVATION ANGLE (AVG OF LOWEST SAT)	30	25	26	18	14	10	8.5
STATIONKEEPING (ALLOWED ECCENTRIC ANOMALLY ERROR)	10	--	--	3	6	3	--

TABLE 11 ORBIT EVALUATION MATRIX

EVALUATION CRITERIA	EVALUATION FORMULA	CANDIDATE ORBITS					
		DELTA	EPSILON	ZETA	SIGMA	THETA	KAPPA
TEST TIME	$\frac{20}{4.2}$ (TT) =	20	16	12	11	10	8
AVE GDOP	3 x 20/AVE GDOD =	3	5	10	14	17	20
MAX GDOP	4 x 10/MAX GDOP =	SPIKE	SPIKE	1	6	8	10
UPLOAD TIME	UPLOAD TIME/3	10	10	7	6	7	8
ELEVATION	30xELEV/26	29	30	21	16	11	10
STATIONKEEPING	10 x SK/6	--	--	5	10	5	--
TOTAL (HIGHEST IS BEST		--	--	56	63	58	--

SELECTED AS BASELINE

3.0 PHASE II STUDIES

Phase II is primarily an Initial Operational Test and Evaluation (IOT&E) phase which culminates in a world wide, continuous two-dimensional navigation capability for a limited group of users. Nine satellites will be deployed in orbital configurations which will attempt to satisfy the requirements listed in paragraphs 1.1.2 and 1.1.3 and repeated below.

Phase II-A - Special Requirements

- 3 x 3 orbit configurations
- 8 hours of continuous test time at WSMR
- GDOP less than 10

Phase II-B - Requirements

- Global 2 satellite coverage
- Minimize orbit maneuvers

Phase II studies have been conducted in order to define the orbital parameters which will best meet these requirements.

3.1 Phase II-A

To meet the GDOP and test time requirements at WSMR, GDOP calculations were run for a 24 hour simulation period for each configuration considered. Frequently more than four satellites are in view and the actual GDOP value calculated at any specific time depends upon which four satellites are being used to make the calculation. Figure 24 shows the programmed algorithm employed to calculate GDOP. The logic generates all possible alternative combinations of four satellites visible at one time. GDOP is calculated for all combinations and the lowest printed. Alternative configurations were generated using two methods. First we examined typical Phase III configuration view times over WSMR (Figure 31) and selected nine satellite subsets which would satisfy view time requirements. Our selection was guided by the fact that 3 x 1 configurations generally give low GDOP.

Of the configurations generated, three are plotted and presented in Figures 25 through 27.

A second method for generating Phase II configurations used the existing Phase I baseline. Satellites were added one by one until a total number of nine was reached. The resulting GDOP Test Time plot is shown in Figure 28.

Visual examination of Figures 25 through 28 show that two configurations (Figures 26 and 27) approximately satisfy Phase II-A requirements. Both show relatively flat GDOP below 10 for 7 hours and 45 minutes.

Elevation angles were briefly considered and it was noted that low GDOP was usually also associated with low angles. No elevation angle trade was conducted, nor was the Csc E penalty incorporated. Realistic GDOP figures are expected to

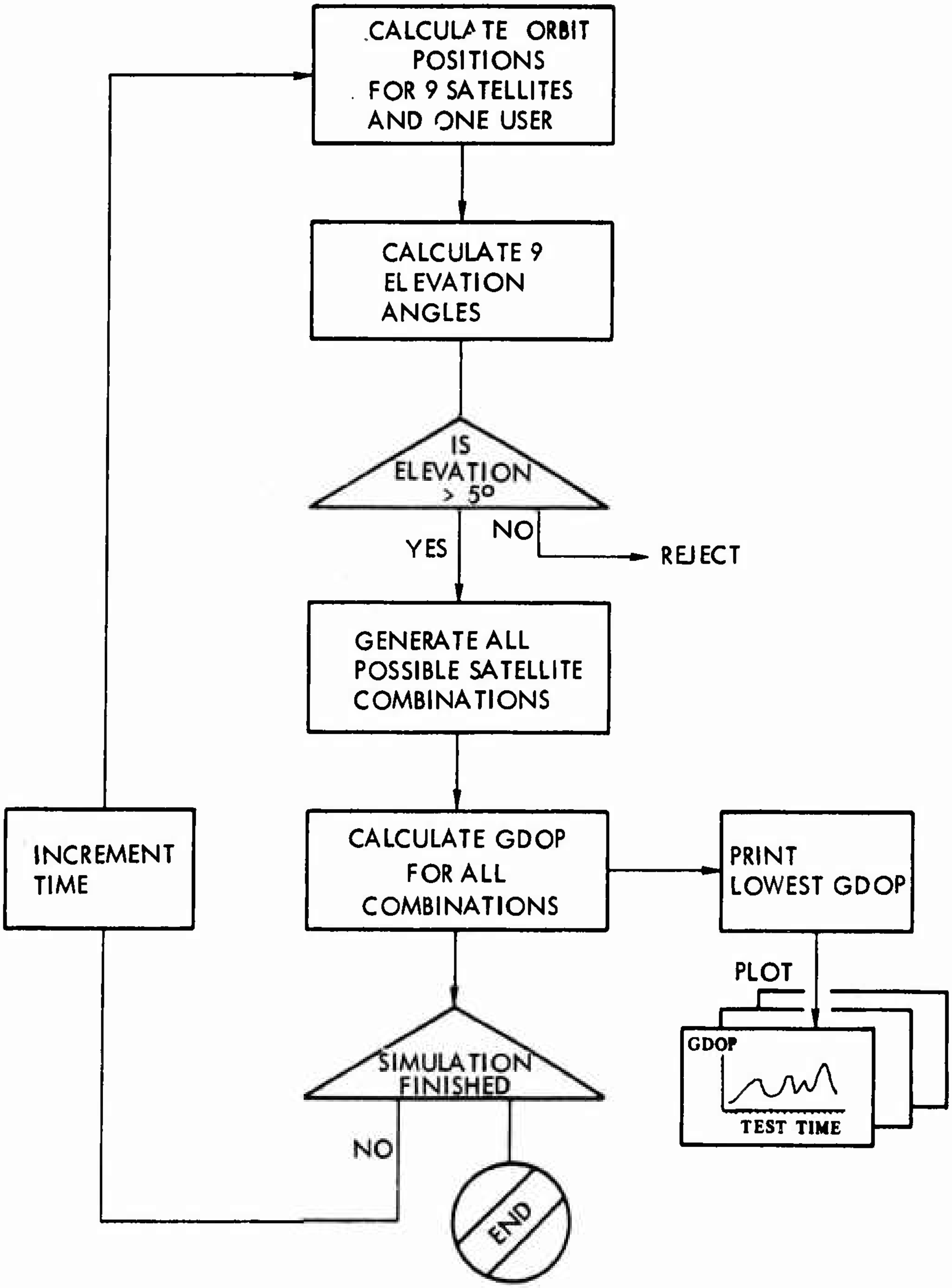
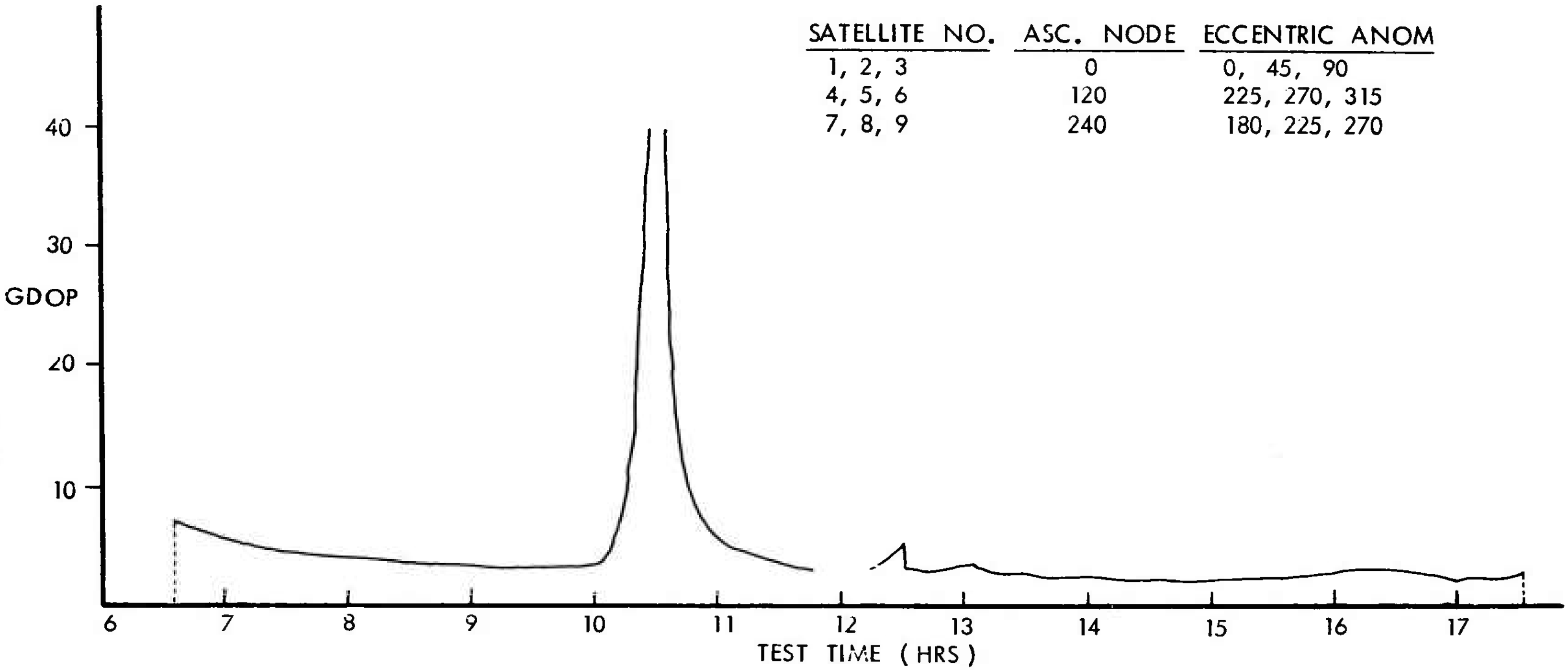
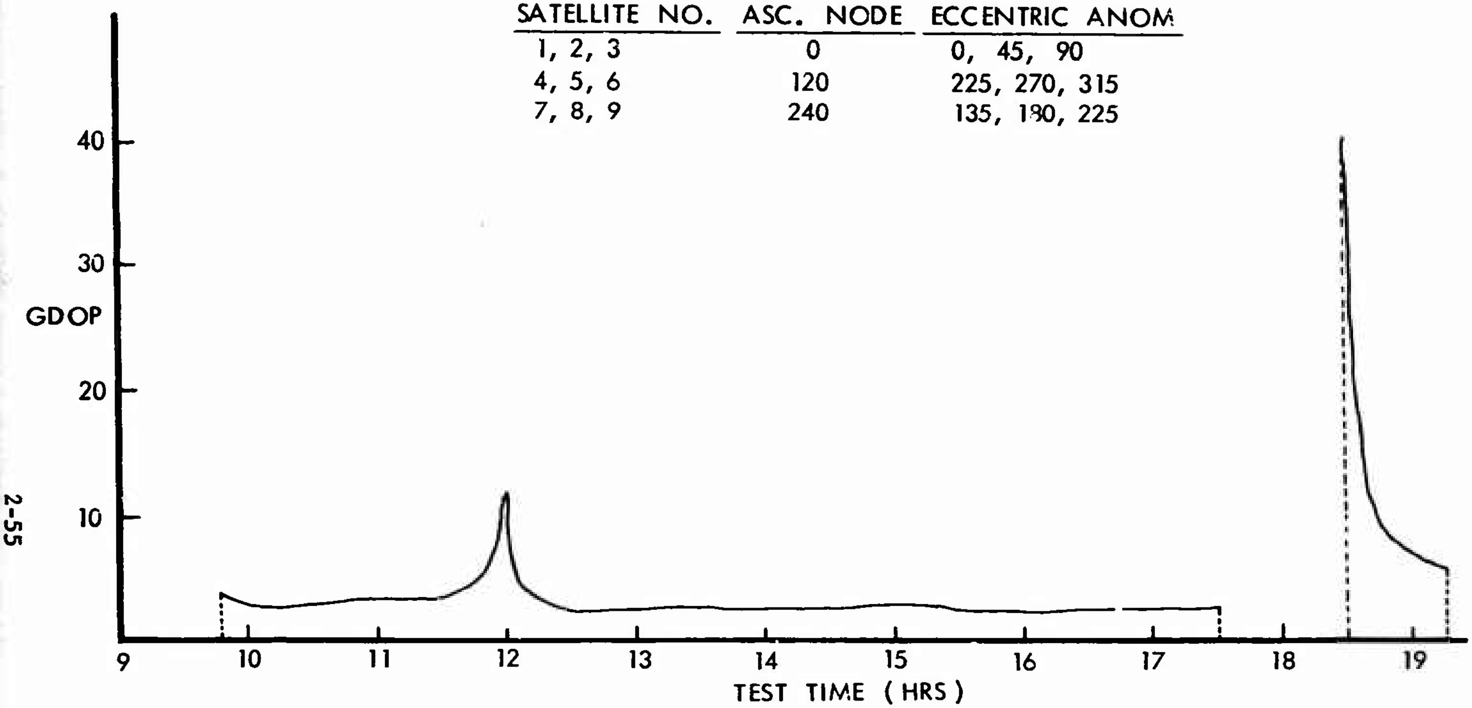


FIGURE 24 Phase II Satellite Selection Approach



SATELLITE NO.	ASC. NODE	ECCENTRIC ANOM
1, 2, 3	0	0, 45, 90
4, 5, 6	120	225, 270, 315
7, 8, 9	240	180, 225, 270

FIGURE 25 GDOP vs Test Time Over Holloman For Phase II-A Configuration IIA - 1



SATELLITE NO.	ASC. NODE	ECCENTRIC ANOM
1, 2, 3	0	0, 45, 90
4, 5, 6	120	225, 270, 315
7, 8, 9	240	135, 180, 225

FIGURE 26 GDOP vs Test Time Over Holloman For Phase II-A Configuration IIA - 2

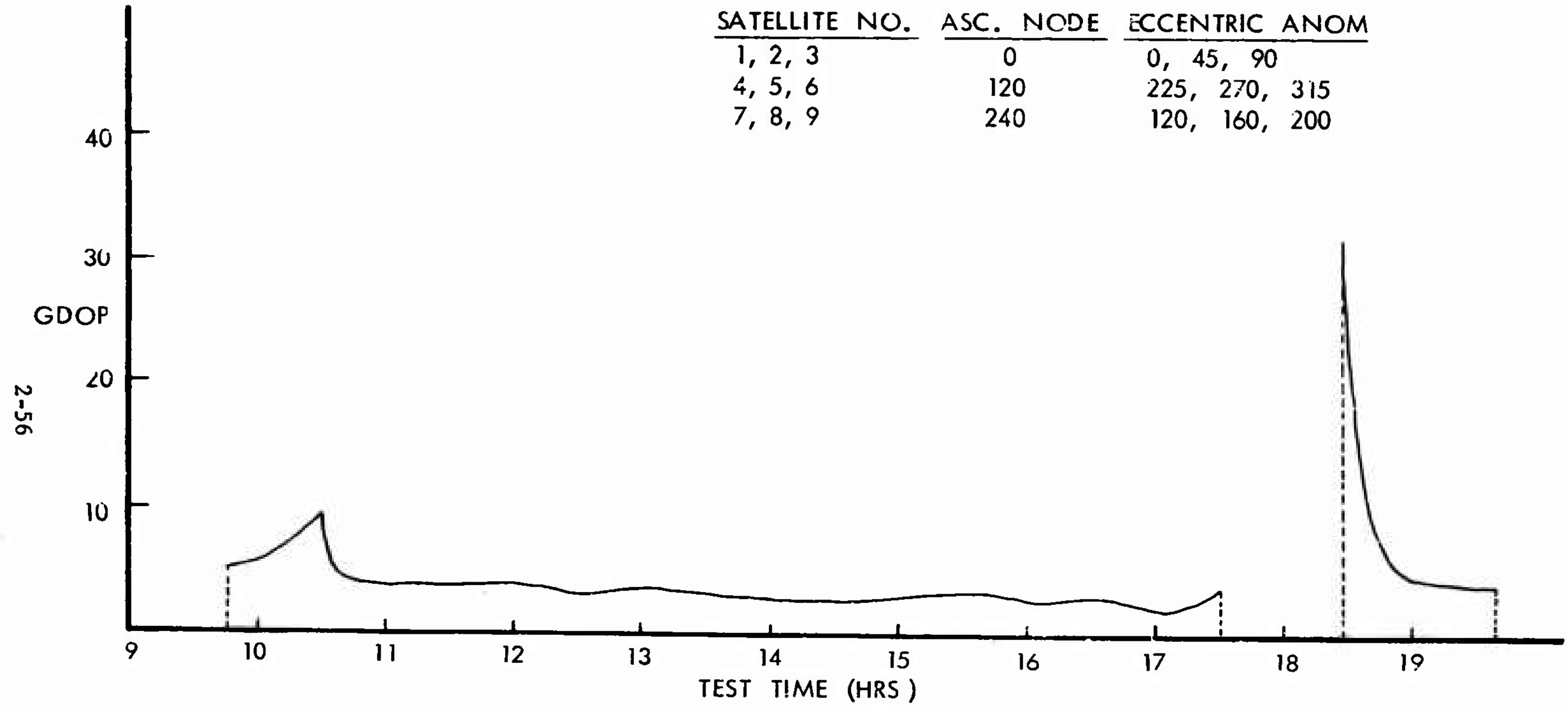
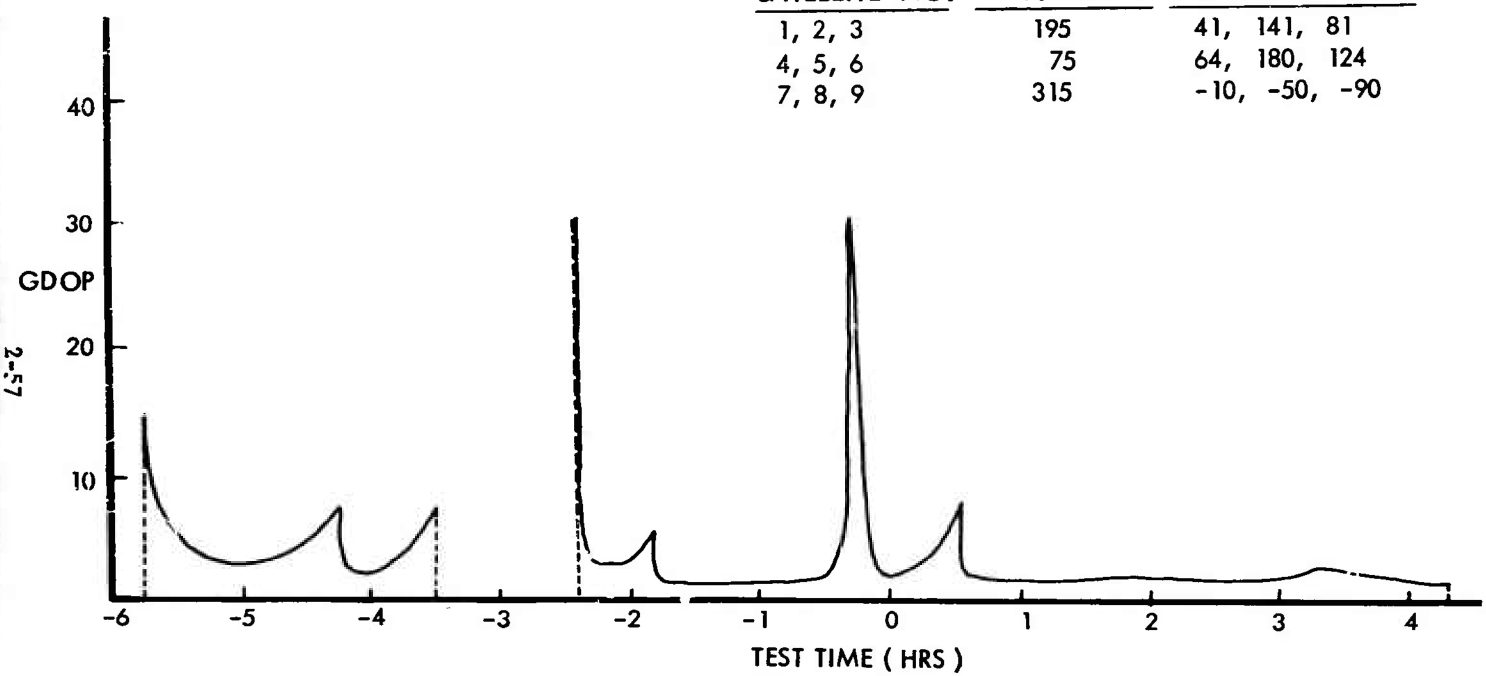


FIGURE 27 GDOP vs Test Time Over Holloman For Phase II-A Configuration IIA - 3



SATELLITE NO.	ASC. NODE	ECCENTRIC ANOM
1, 2, 3	195	41, 141, 81
4, 5, 6	75	64, 180, 124
7, 8, 9	315	-10, -50, -90

FIGURE 28 GDOP vs Test Time Over Holloman For Phase II-A Configuration IIA - 4

be somewhat higher than those presented; however, no distinct disadvantage to either configuration (Figures 26 and 27) was noted. User/Satellite elevation angle probability distributions for Phase II-A appear in Appendix D.

Fuel requirements for shifting satellites from Phase I to Phase II stations were calculated (see Appendix C). Again no advantage to either configuration is obvious.

Configuration Figure 26 was finally chosen as a baseline for Phase II-A and presented in Table 2 of Section 1. Since the nine satellites are a subset of the Phase III OMEGA (3 x 8) configuration, the configuration was named "OMEGA-2A."

3.2 Phase II-B Studies

During Phase II-B nine orbiting satellites will be distributed to provide world wide two satellite coverage. To analyze alternative configurations, a timeshare computer program has been developed which generates a world wide satellite visibility coverage map. The program calculates the number of hours per day that X or more satellites are visible from any point on the earth.

We expected to achieve optimum two satellite coverage using highly symmetric 3 x 3 configurations.

Three candidate Phase II-B configurations (Table 12) have been investigated for their two satellite coverage characteristics. All configurations have three 12 hour, 63^{o} inclination orbits with plane spacing of 120 degrees, and with 120^{o} satellite separation within the orbit planes. The difference between candidates is only in the relative satellite phase. In Configuration 1, satellites in each orbit plane cross the equator at the same time. In Configuration 2, the satellite equator crossings are staggered by fifteen degrees. In Configuration 3, they are staggered by 30 degrees.

Results of two satellite coverage runs show that all candidates give world wide two satellite coverage. It is therefore concluded that any 3 x 3 120^{o} symmetric configuration is an acceptable Phase II-B candidate if two satellite coverage is the determining criteria, and Configuration 1 was chosen as a baseline. Since this configuration was a subset of a 3 x 9 configuration designated "GAMMA", we have named this 3 x 3 configuration "GAMMA-2B".

The following performance characteristics of the above chosen baseline were investigated in detail.

- Compatibility with Phase II-A, Phase III
- Three satellite coverage
- Four satellite coverage and GDOP

TABLE 12 PHASE II-B CANDIDATE CONFIGURATION

CONFIGURATION 1

ARGUMENT OF PERIGEE DEG.	ECCENTRIC ANOMALY DEG.	ECCENTRICITY	INCLINATION DEG.	ASCENDING NODE DEG	SEMI MAJOR AXIS NMI
0.	0.	0.	63.0000	195.0000	14342.0000
0.	120.0000	0.	63.0000	195.0000	14342.0000
0.	240.0000	0.	63.0000	195.0000	14342.0000
0.	0.	0.	63.0000	75.0000	14342.0000
0.	120.0000	0.	63.0000	75.0000	14342.0000
0.	240.0000	0.	63.0000	75.0000	14342.0000
0.	0.	0.	63.0000	315.0000	14342.0000
0.	120.0000	0.	63.0000	315.0000	14342.0000
0.	240.0000	0.	63.0000	315.0000	14342.0000

CONFIGURATION 2

ARGUMENT OF PERIGEE DEG.	ECCENTRIC ANOMALY DEG.	ECCENTRICITY	INCLINATION DEG.	ASCENDING NODE DEG	SEMI MAJOR AXIS NMI
0.	0.	0.	63.0000	195.0000	14342.0000
0.	120.0000	0.	63.0000	195.0000	14342.0000
0.	240.0000	0.	63.0000	195.0000	14342.0000
0.	15.0000	0.	63.0000	75.0000	14342.0000
0.	135.0000	0.	63.0000	75.0000	14342.0000
0.	255.0000	0.	63.0000	75.0000	14342.0000
0.	30.0000	0.	63.0000	315.0000	14342.0000
0.	150.0000	0.	63.0000	315.0000	14342.0000
0.	270.0000	0.	63.0000	315.0000	14342.0000

CONFIGURATION 3

ARGUMENT OF PERIGEE DEG.	ECCENTRIC ANOMALY DEG.	ECCENTRICITY	INCLINATION DEG.	ASCENDING NODE DEG	SEMI MAJOR AXIS NMI
0.	0.	0.	63.0000	195.0000	14342.0000
0.	120.0000	0.	63.0000	195.0000	14342.0000
0.	240.0000	0.	63.0000	195.0000	14342.0000
0.	60.0000	0.	63.0000	75.0000	14342.0000
0.	180.0000	0.	63.0000	75.0000	14342.0000
0.	300.0000	0.	63.0000	75.0000	14342.0000
0.	30.0000	0.	63.0000	315.0000	14342.0000
0.	[illegible].0000	0.	63.0000	315.0000	14342.0000
0.	[illegible]000	0.	63.0000	315.0[illegible]0	14342.0000

Figure 29 shows the visibility contours for three-satellite global coverage. Both the north and south poles as well as selected regions on the equator see three satellites for 24 hours per day. Minimum ~14 hr/day coverage occurs in regions spaced 60° apart in longitude, at ~ 30° north and south latitude. The coverage pattern depends only upon the relative satellite symmetry and can be shifted east or west by changing nodes and/or anomalies.

Table 13 shows the coverage for four satellites. Due to the expense of generating a total world map, only one sixth of the earth has been calculated. Other points can be easily derived from symmetry. The pattern repeats each 120° in the southern hemisphere and reflects into the northern hemisphere shifted by ± 30° longitude. For example, WSMR (New Mexico) is equivalent to a user at -33 latitude, 104 longitude. Elevation angle distributions appear in Appendix D.

A detailed GDOP plot for WSMR as well as a view time histogram has been included in Figure 30. This figure shows numerous disjointed regions during which four satellites are in view. GDOP numbers are all low; however, no single extended test period can be expected.

Fuel requirements for changing stations from Phase II-A to Phase II-B have been calculated according to the procedure outlined in Appendix C. The results are shown in column eight Table 3 in Section 1. Since the stations for Phase II-B are a subset of the final Phase III configuration, additional fuel allocations will be determined by stationkeeping requirements only, and are expected to add an additional 1 lb of hydrazine per year per satellite to the fuel budget.

4.0 PHASE III

A 24 satellite 3 x 8 configuration designed to provide continuous four satellite global coverage had been chosen as the Phase III baseline before the initiation of this study. This configuration has been named "OMEGA".

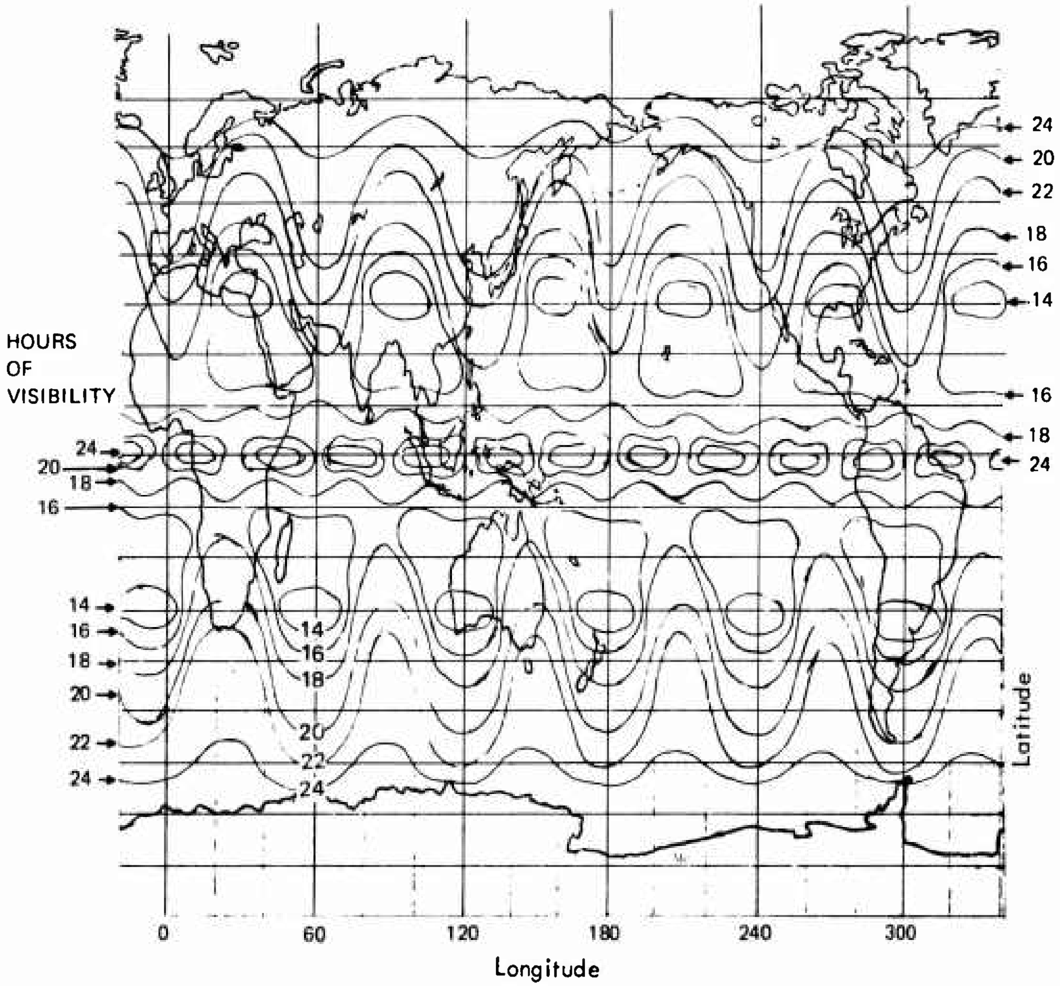


FIGURE 29 WORLD VISIBILITY CONTOURS
Number of Hours Per Day That 3 Satellites Are Visible
(Phase II-B Candidate Configuration 1)

TABLE 13 4 SATELLITE COVERAGE

ARGUMENT OF PERIGEE DEG.	ECCENTRIC ANOMALY DEG.	ECCENTRICITY	INCLINATION DEG.	ASCENDING NODE DEG.	SEMI MAJOR AXIS NMI
0.	0.	0.	63.0000	195.0000	[illegible]
0.	120.0000	0.	63.0000	195.0000	[illegible]
0.	240.0000	0.	63.0000	195.0000	[illegible]
0.	0.	0.	63.0000	75.0000	[illegible]
0.	120.0000	0.	63.0000	75.0000	[illegible]
0.	240.0000	0.	63.0000	75.0000	[illegible]
0.	0.	0.	63.0000	315.0000	[illegible]
0.	120.0000	0.	63.0000	315.0000	[illegible]
0.	240.0000	0.	63.0000	315.0000	[illegible]

VIEW TIME IN A 24hr PERIOD

LATITUDE / LONGITUDE	-90	-75	-60	-45	-30	-15	00
10.	3.7	8.2	8.7	7.2	5.5	5.5	7.0
20.	3.7	3.7	7.5	4.5	3.5	4.7	7.0
30.	3.7	3.0	3.5	3.0	2.0	2.2	6.
40.	3.7	7.5	8.0	4.7	3.0	4.5	6.7
50.	3.7	8.5	8.5	7.2	5.2	5.2	6.7
60.	3.7	9.0	9.2	9.0	6.5	6.0	0.
70.	3.7	9.2	9.0	7.2	5.2	5.2	6.7
80.	3.7	8.7	8.0	4.5	3.2	4.5	6.7
90.	3.7	[illegible]	8.7	3.7	2.0	2.2	6.
100.	3.7	8.0	7.5	4.7	3.0	4.5	6.7
110.	3.7	9.7	9.7	7.2	X 5.5	5.7	6.7
120.	3.7	6.0	9.2	7.7	6.0	6.5	6.
130.	3.7	8.2	8.7	7.2	5.5	5.5	7.0

X = EQUIVALENT HOLOMAN USER

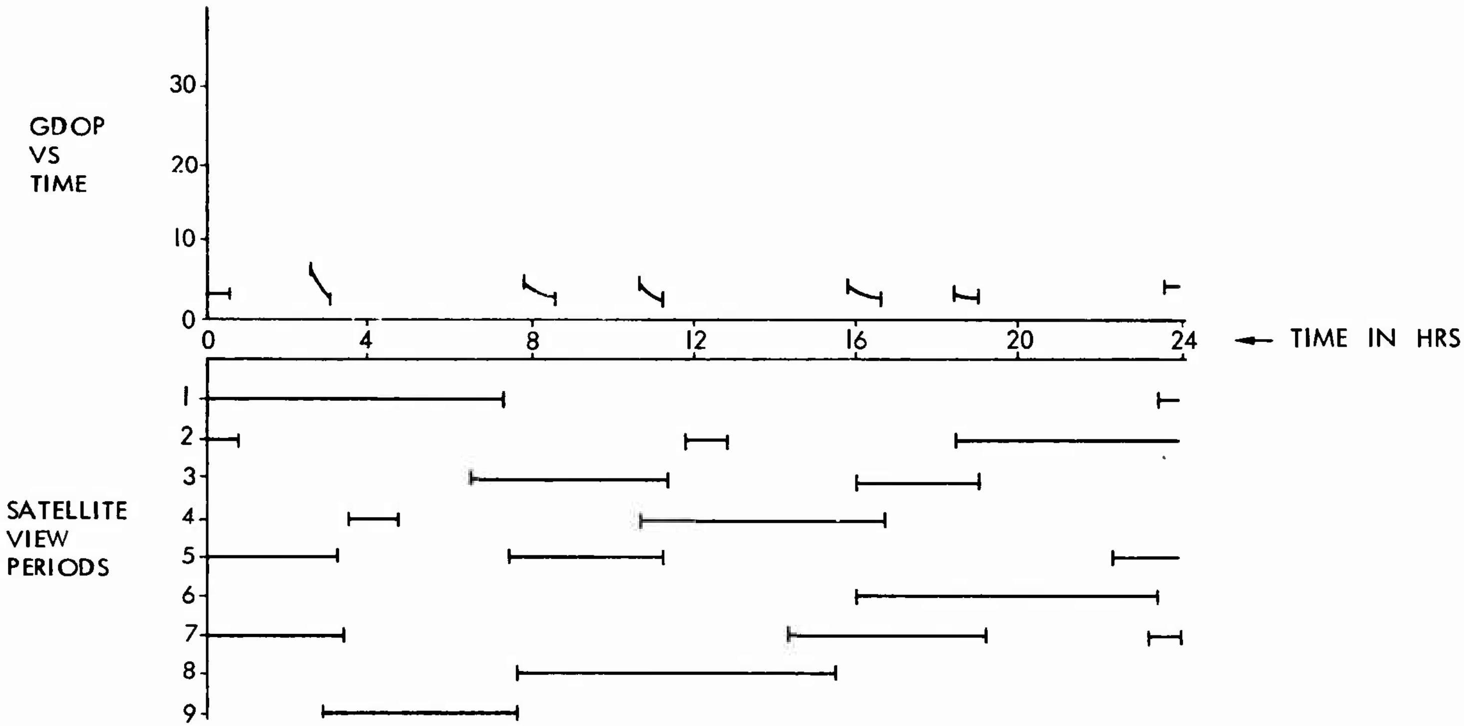


FIGURE 30 GDOP and Viewtime Histogram Over Holloman N. M.

Recent publications[1] verify the expectation that a 24 satellite configuration will provide adequate coverage, and Table 14 shows that five or more satellites are always seen from a sample set of ground stations. Though no GDOP analysis has been done, experience from Phase II-A would lead us to expect low GDOP whenever coverage allows a selection of four satellite combinations out of five or more in view.

Figure 31 shows a bargraph of view times over the WSMR test site. Subsets of this configuration were chosen as candidate Phase II configurations. Orbital parameters are presented in Table 4 of Section 1. User/Satellite elevation angle probability distributions appear in Appendix D.

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[1] Time-in-View Bargraphs for Baseline Orbits, W. T. Picciano, Philco-Ford Technical Memo GPS-TM-005, Jan 28, 1974

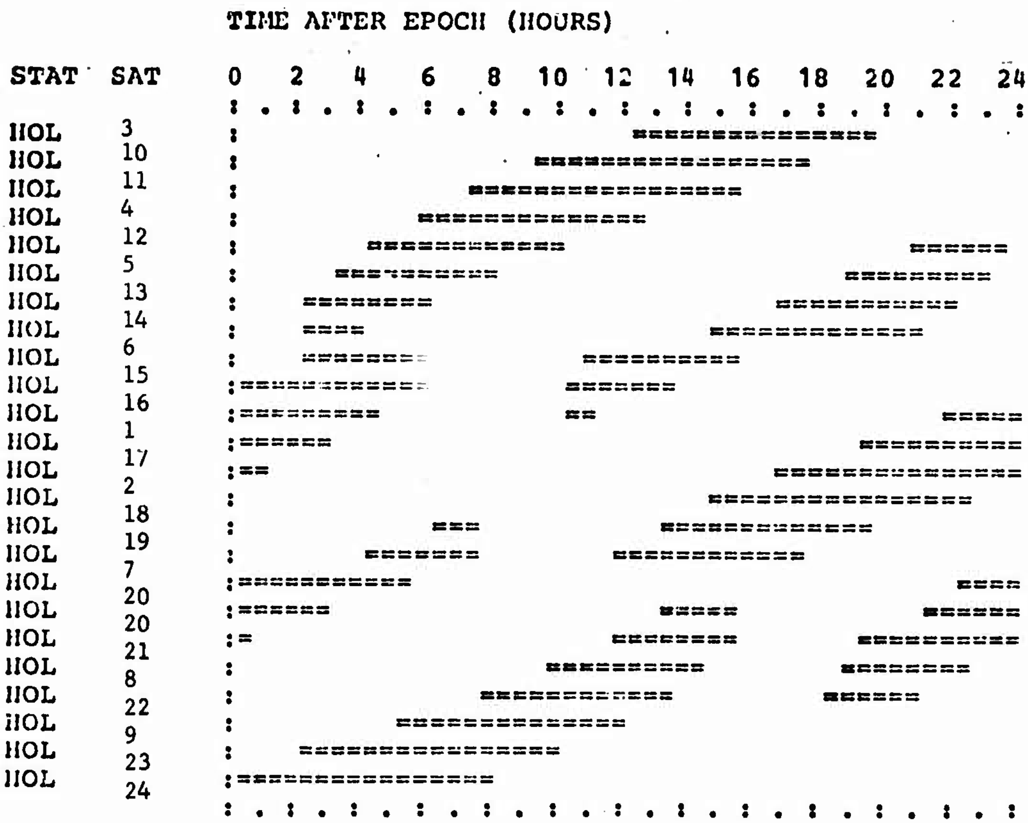
TABLE 14

TIME N OR MORE SATELLITES IN VIEW

TABLE OF FRACTIONS OF A DAY THAT N OR MORE SATELLITES ARE IN VIEW

STAT	N=0	N=1	N=2	N=3	N=4	N=5	N=6	N=7	N=8	N=9	N)10
SAC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.823	.663	.392	.045
LOR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.885	.736	.438	.063
SPO	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.868	.469	.049
MIN	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.920	.771	.556	.208
MUG	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.694	.604	.326	.021
VIR	1.00	1.00	1.00	1.00	1.00	1.00	.93	.750	.608	.285	.045
RIC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.733	.594	.333	.028
YUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.729	.604	.344	.014
SAM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.788	.667	.326	.000
BOS	1.00	1.00	1.00	1.00	1.00	1.00	.95	.840	.688	.396	.139
GUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.806	.667	.330	.007
HOL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.726	.604	.319	.017
HUL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.740	.611	.302	.017
IOS	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.889	.330	.035
KOD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.997	.712	.156
POG	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.997	.816	.160
VTS	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.708	.628	.354	.014

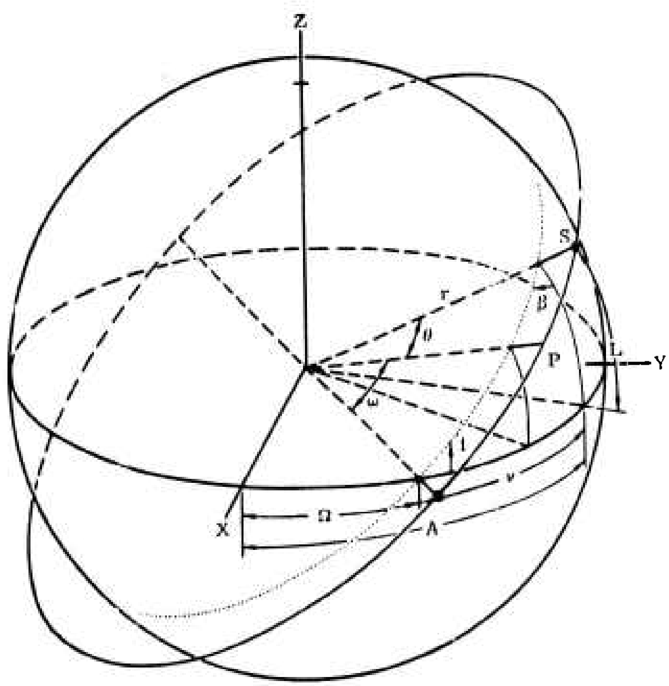
Figure 31 Time In View Bar Graphs For Phase III Baseline Over WSMR



APPENDIX A
DEFINITION OF TERMS

<u>Orbital Parameters</u>

Ω	Longitude of ascending node
i	Inclination angle of the orbit to the equatorial plane
r	Orbital radius
ω	Argument of perigee
θ	Eccentric anomaly
P	Perigee
S	Satellite position



USER TERMS

$$\sum_{j=1}^{3} (X_{ij} - U_j)^2 = (r_i - b)^2$$

(User Equation)

The geometric relationship between user position, four satellites and four pseudorange measurements.

X_{ij}	The jth component of position of the ith satellite.
U_j	The jth component of position of the user.
r_i	The pseudorange measurement from the user to the ith satellite
b	Clock user bias

$$GDOP = (G^T G)^{-1} = \sum \frac{\partial U_j}{\partial X_{ij}} \frac{\partial U_j}{\partial X_{ij}}$$

sum over coordinates and satellites

G	The matrix of coefficients derived by linearizing the user equation

APPENDIX B
EQUIVALENT ORBIT CONFIGURATIONS

Consider Figure 1 in Section 1.1 above, which shows a world map with a ground track for a 12 hour synchronous orbit. A satellite could be located on any point, A, of the ground track making one complete revolution with respect to the earth. A second satellite A', moving on the same ground track would move maintaining exactly the same geographic relation with respect to all points on the ground as satellite A. The difference is only the time at which the relation occurs. Hence every measurable geometric quantity like GDOP, elevation and azimuth angle view time are achievable by a whole family of satellite configurations differing from each other only by a time displacement.

The relationship between two equivalent satellite configurations can be expressed mathematically as:

$$\text{Node}_i + 15^\circ/\text{hr. time} = \text{Node}'_i$$

$$\text{Anomaly}_i - 30^\circ/\text{hr. time} = \text{anomaly}'_i$$

where

Node_i = longitude of ascending node of the ith satellite of the reference configuration.

Anomaly_i = Eccentric anomaly of the ith satellite of the reference configuration.

Node'_i = longitude of ascending node of the ith satellite of equivalent configurations.

$\text{Anomaly}'_i$ = longitude of ascending node of the ith satellite of equivalent configurations.

Time	=	time difference between two configurations.	

This relationship has been graphed in Figure B-1. Diagonal lines represent all node and anomaly combinations which are equivalent. As an example, the four satellite configuration, SIGMA, from Phase I is shown as small circles along with the equivalent configuration, expressed in Phase III reference ascending nodes, shown as small x.

Numerically, configuration SIGMA:

Eccentric Anomaly	41	81	64	124	Deg
Ascending Node	195	195	75	75	Deg

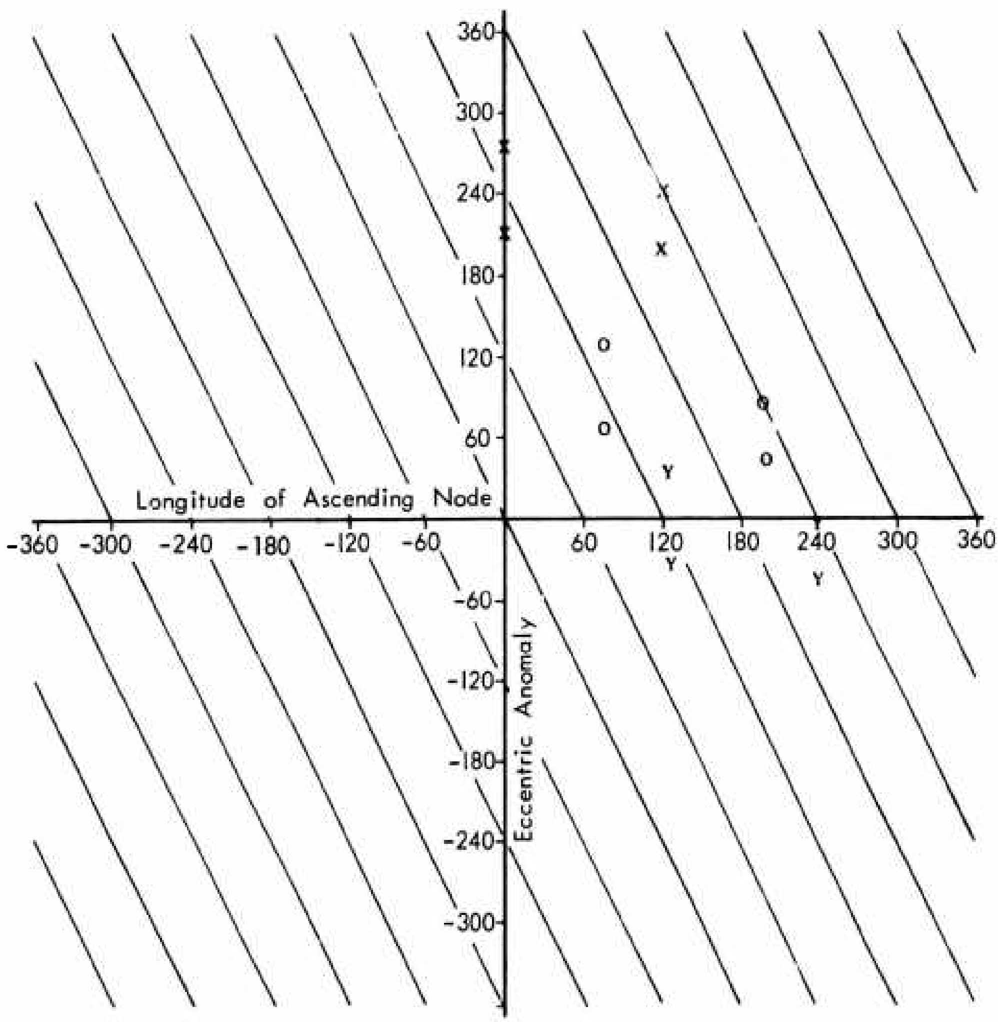
is equivalent to a configuration defined by:

Eccentric Anomaly	214	274	191	231	Deg
Ascending Node	0	0	120	120	Deg

and a configuration:

Eccentric Anomaly	-26	34	-49	-9	Deg
Ascending Node	120	120	240	240.	Deg

FIGURE B 1 Equivalent Satellite Configuration



O - SIGMA PHASE I CONFIGURATION

X - EQUIVALENT SIGMA

Y - EQUIVALENT SIGMA

APPENDIX C

FUEL COST FOR ORBITAL MANEUVERS

The mission sequence for GPS may require a change of semi-major axis, mean anomaly, ascending node and/or inclination. The amount of fuel required for a given maneuver can be calculated from graphs presented in this appendix.

Changes in semi-major axis for circular orbits require two rocket firings along the velocity vector. The first firing injects the space vehicle into an eccentric transfer orbit and occurs at apogee (perigee). The second firing occurs at perigee (apogee) and recircularizes the orbit. The circular orbit velocity semi-major axis relation is:

$$1/2\ V^2 = \frac{MG}{r}$$

where

MG	=	Mass of Earth x gravity constant
r	=	Semi-major axis
V	=	Orbital velocity

the incremental relations are derived by differentiation to give:

$$\Delta V = -\sqrt{\frac{MG}{2r^3}}\ \Delta r$$

where

ΔV	=	velocity increment
Δr	=	semi-major axis change

For 14341.5 nm orbit, the value of the quantity under the square root is 0.44 ft per second per nm, and remains approximately constant for directions of a hundred miles.

In Figures C-1 and C-2 the lower left hand graph shows the relationship between velocity increment and semi-major axis change. Figure C-1 is a small scale version of Figure C-2, convenient for perturbation and fine orbit tuning.

The converversion from required velocity increment to lbs. of fuel required is given by:

$$M \Delta V = I_{sp} W$$

where

I_{sp} = 200 slug ft/sec for Hydrazine

M = Spacecraft weight in slugs $\simeq 20$

W = Fuel weight in lbs.

Substituting and solving gives:

$$\Delta V = 10W$$

So a 10 ft/sec change would require 1 lb. of fuel.

Corrections and reposition of the eccentric anomaly usually requires a semi-major axis change, followed by a drift period, followed by a second semi-major axis change, to return to the old orbit. The amount of fuel required will depend upon how rapidly the maneuver is to be executed. Figures C-1 and C-2 are intended to aid in the calculation.

Consider the following example: Satellite 1 Phase I has an ascending node 0 and anomaly 191 and is to be moved to a Phase II station at node 0 and anomaly 45. The total maneuver is a correction 146 degrees. Assume it is to be executed

in one month. Entering Figure C-2 with an eccentric anomaly drift of 146 (dotted line), go up to the drift period line marked "1 month." Cross over the period axis just under -5 min/orbit which corresponds to about 60 nm change in semi-major axis. This requires a velocity increment of 30 ft/sec or 3 lbs. of fuel. Since the axis change must be carried out twice, the total fuel requirement is 6 lbs. In practice, somewhat more fuel is required to correct thruster resolution and pointing uncertainties.

For convenience, the intermediate steps required to make orbital maneuvers in the above mentioned nomograms have been eliminated in Figure C-3, where eccentric anomaly change is given directly in terms of hydrazine fuel costs for a GPS satellite. Figure C-3 was used to calculate fuel costs presented in Section 1.1.

Fuel Costs for Plane Changes. Plane changes and inclination changes can be derived from Newton's second law.

$$\frac{d\ell}{dt} = F \times r$$

ℓ = orbital angular momentum = (mvr)

F = I_{sp} . W/dt force applied at spacecraft perpendicular to orbit plane

A small angular change is:

$$\Delta\theta = \frac{F \times r}{\ell}\,dt = \frac{I_{sp}\ W}{m\ v} \times 57.3^{\circ}/\text{rad}$$

Evaluating for I_{sp} = 200, m = 20 slug

V = 12,000 ft/sec gives:

$$\Delta\theta = .0475\ W$$

or 21 lbs. of Hydrazine per degree. Clearly no plane changes can be tolerated in GPS.

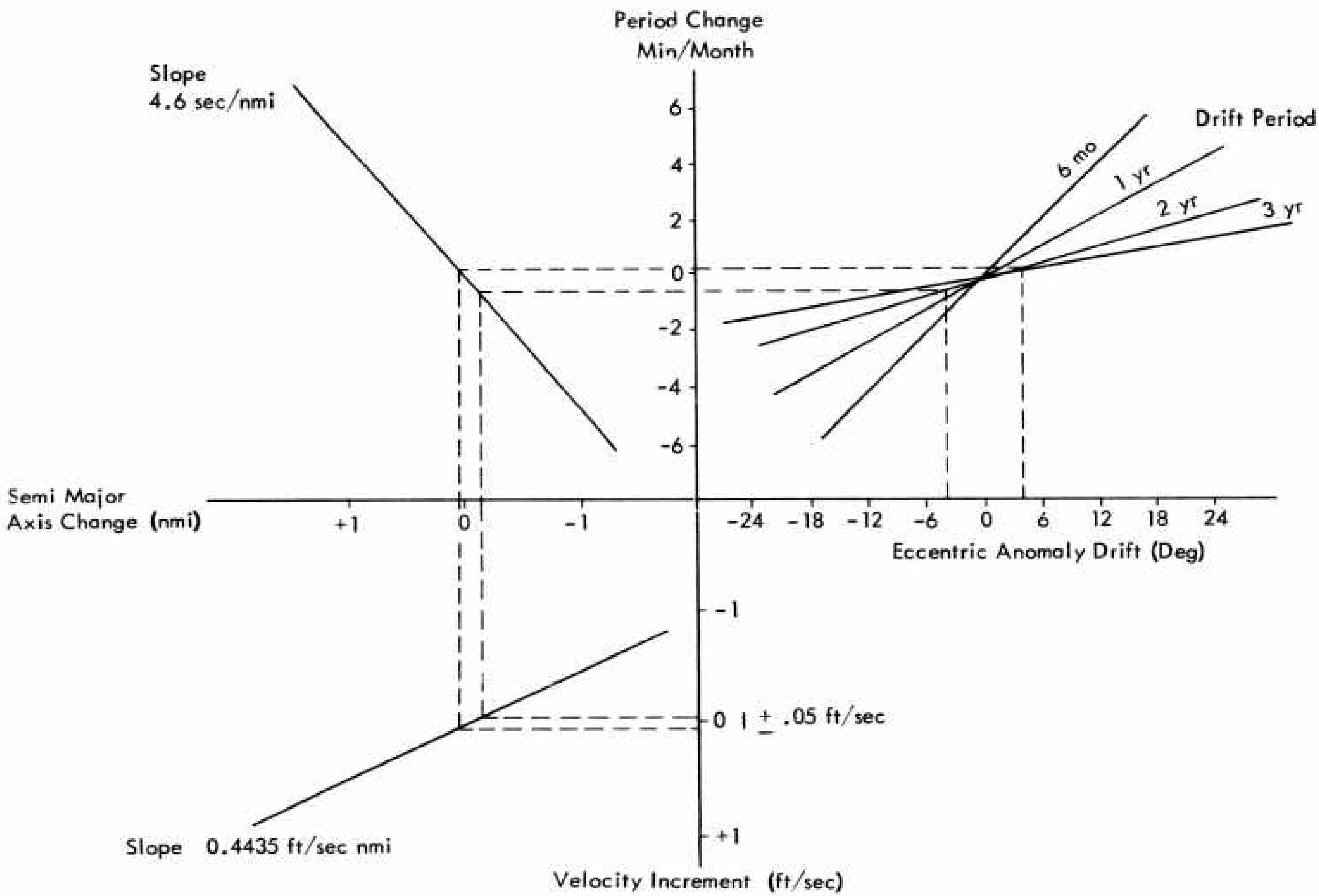


Figure C1 Velocity Increment To Eccentric Anomaly Drift Nomogram

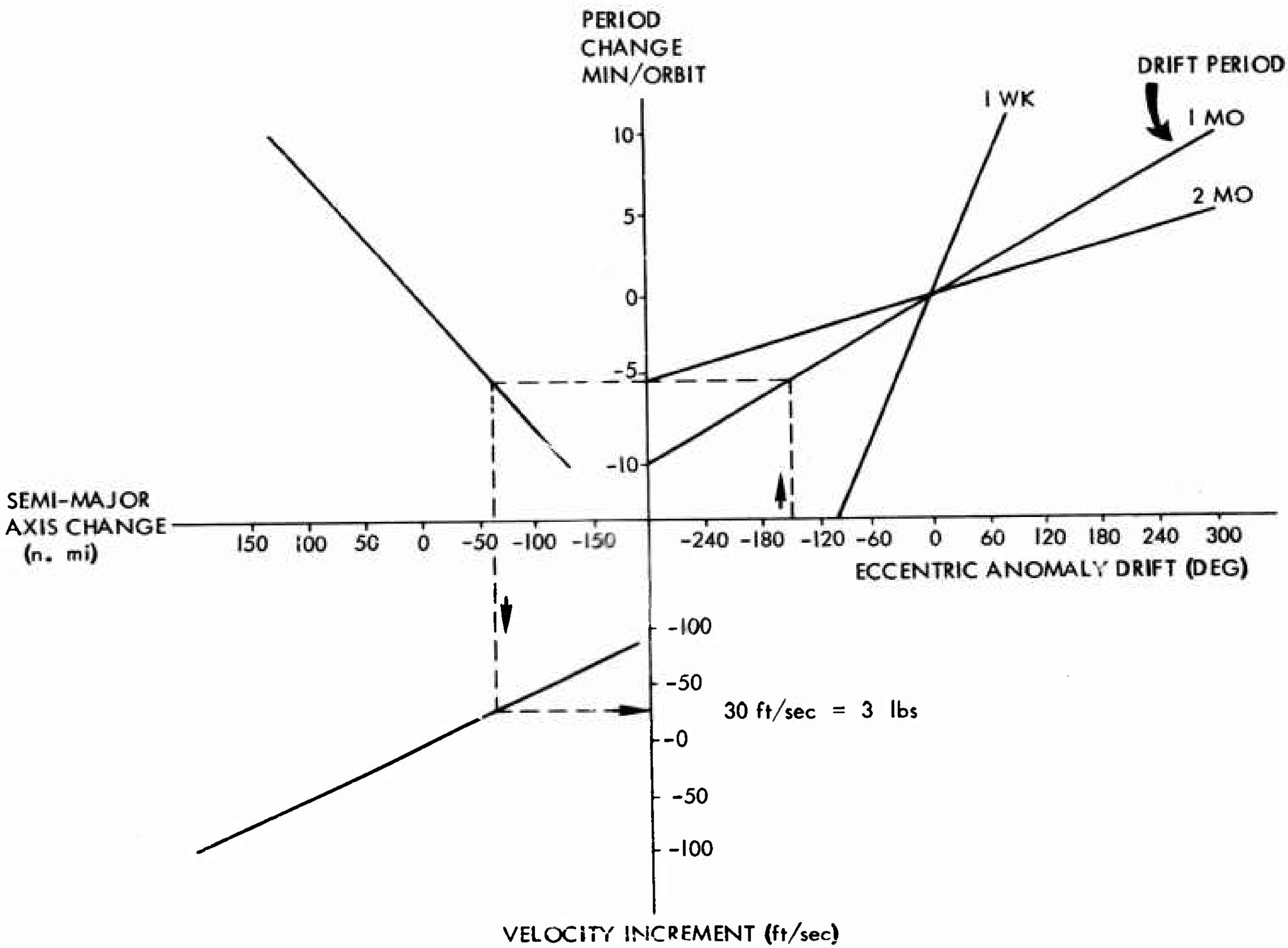


Figure C2 VELOCITY INCREMENT TO ECCENTRIC ANOMALY DRIFT NOMOGRAM

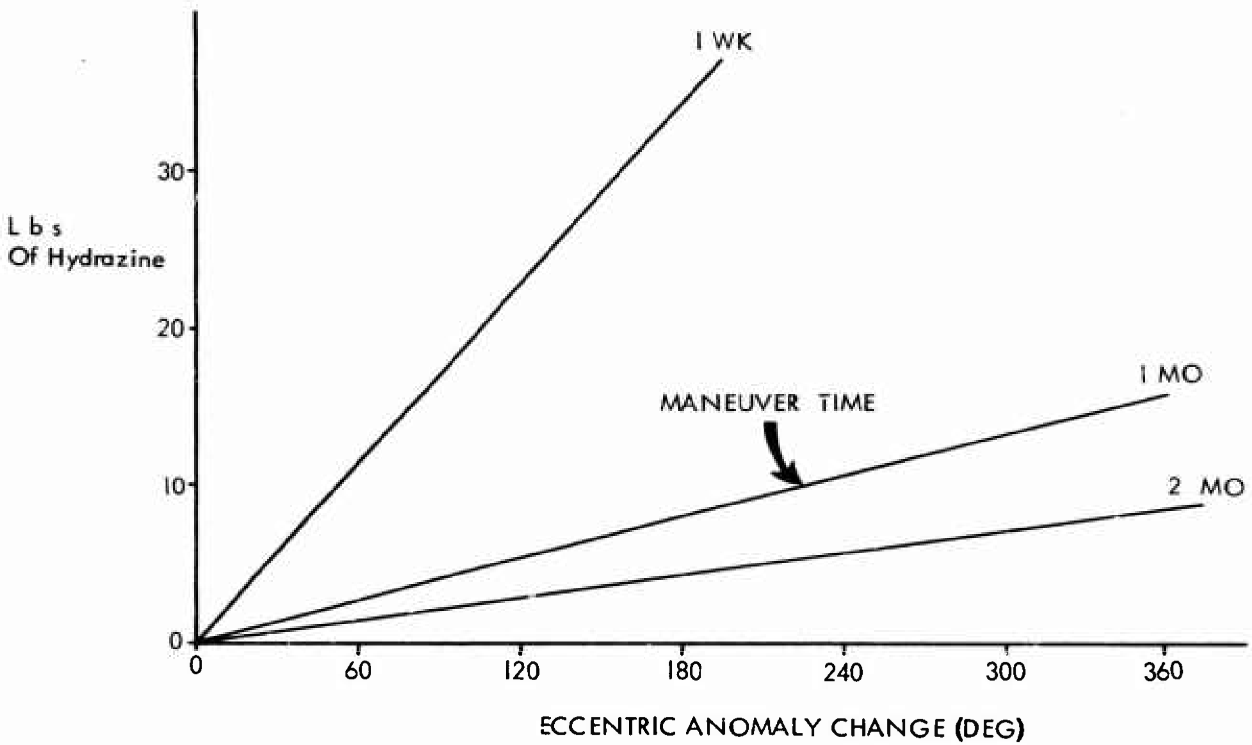


Figure C3 - FUEL COST FOR ANOMALY SHIFT MANEUVER ON GPS 12 hr. 20 slug SATELLITES

APPENDIX D

ELEVATION ANGLE PROBABILITY DISTRIBUTIONS

Elevation angle statistics were derived from TRACE satellite-pass output data. Interpolated elevation angles were sampled at 5 degree intervals to determine the time spent in each interval.

Figure D-1 shows the Phase I elevation angle probability distribution at four selected ground stations (LOR, HUL, KOD, and MUG) for the SIGMA satellites. All stations are seen to experience a similar ele ation angle distribution.

Figure D-2 compares elevation angle distributions during the test period only (at WSMR) between Phase I, II-A, II-B, and III users. Overall test periods will vary in length (as indicated) and the graph axis is accordingly presented in percent of total time for each configuration test period.

PHILCO
Philco-Ford Corporation
Western Development Laboratories Division

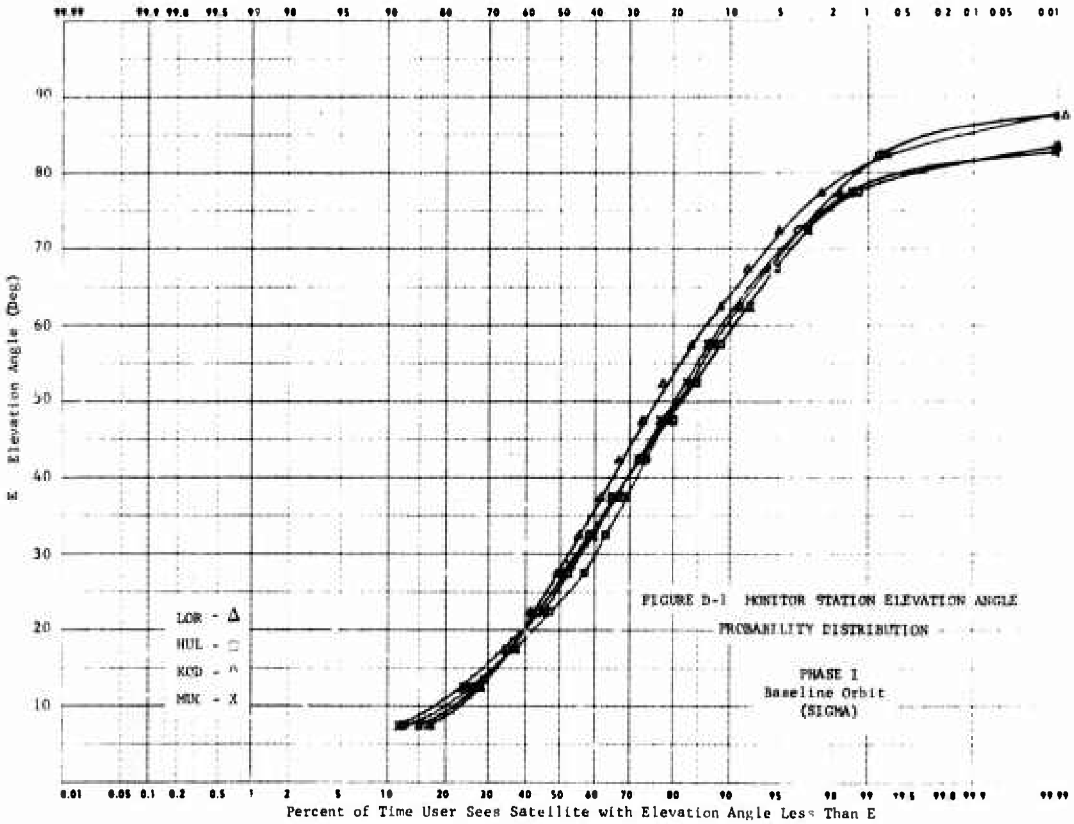


FIGURE D-1 Monitor Station Elevation Angle Probability Distribution

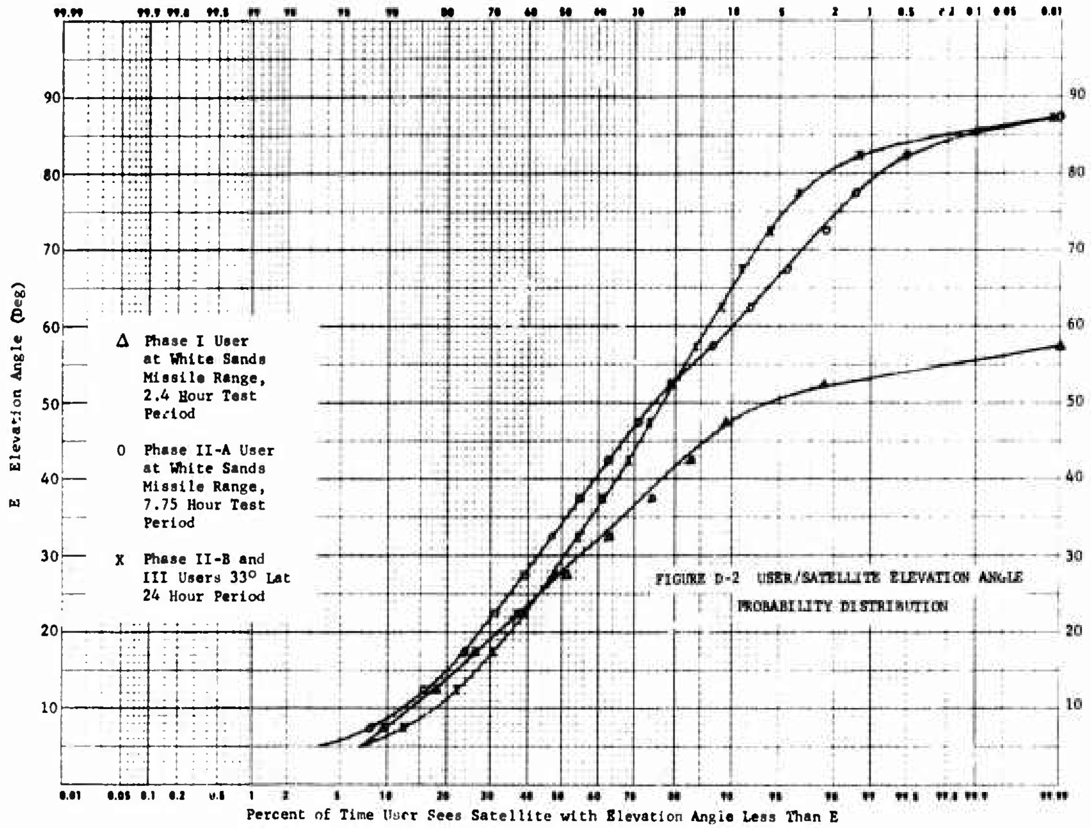


FIGURE D-2 User/Satellite Elevation Angle Probability Distribution

REPORT C 3

TELECOMMUNICATIONS SYSTEM COST ANALYSIS

REPORT C 3

TELECOMMUNICATIONS SYSTEM COST ANALYSIS

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TOPICS ADDRESSED

REPORT C 3

TELECOMMUNICATIONS SYSTEM COST ANALYSIS

LIST OF ILLUSTRATIONS

Telecommunications System Cost Analysis

The annual costs of various telecommunications facilities are examined in this study. The analysis was directed toward potential Master Control Station and Monitor Station sites. Included in the analysis are costs for dedicated lines, dial-up lines, WATS lines, and shared NAG lines. The analysis is composed of two areas. The first area compares the various telecommunication links with respect to the different potential line types. Within this area, the shared NAG lines approach is examined in further detail. The second area examines the dial-up annual costs as a function of several store and forward intervals of time. **Note that this analysis is performed for the NAG configuration baseline and is included here for completeness as well as representing valuable data for further such analyses.**

Analysis of Telecommunication Links

The telecommunications system in this analysis includes a Master Control Station (MCS) located at Pt. Mugu and Monitor Stations (MON) located at Pt. Mugu, Hawaii, Alaska, and Maine. In addition, a Remote Computer Facility (RCF) was located at NWL in Virginia. The satellite upload function was assumed to be contained within the MON located at Elmandorf, Alaska.

In this analysis the telecommunication links are separated functionally. Therefore, each link is analyzed separately, with the only exception being the functionally identical links to Hawaii and Maine. The communication costs which are listed in the analysis are derived from Tables 3-4 through 3-6

The types of communications equipment which is required for interconnection with the various links is shown in Figure 3-1. A description of the communications equipment for each link is also included in this section.

Tables 3-1 through 3-3 present the communication link analyses for Hawaii and Maine, Elmendorf and Virginia.

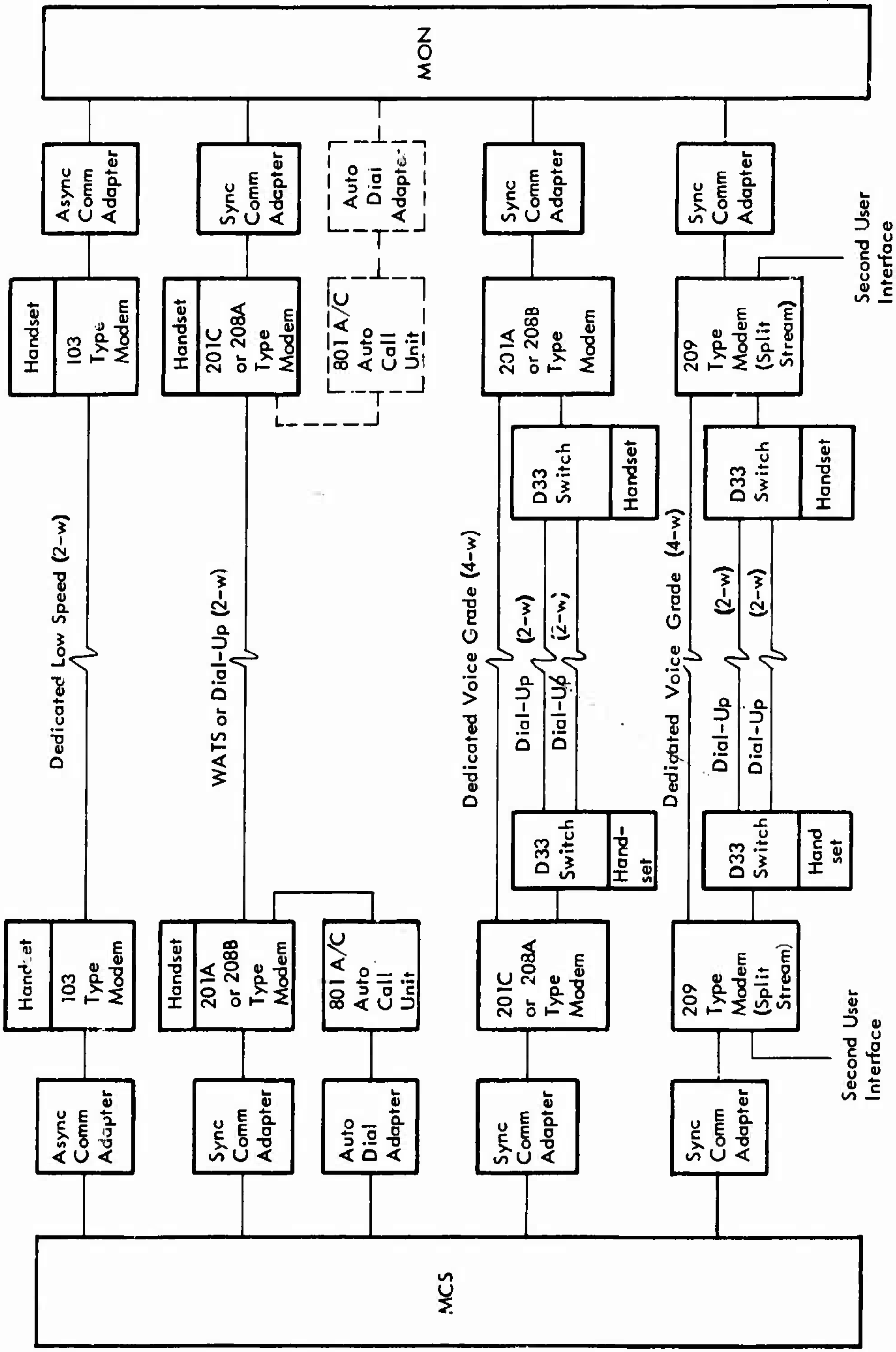


FIGURE 3-1 Types of Communication Equipment Required

	Real Time Operation: Dedicated			WATS			Dialup	
	Dedicated			WATS			Dialup	
Line Costs								
Haw/Mugu	150 BPS	$41,500		Not Available				$512,500
Ma/Mugu	150 BPS	19,300		Full Time	$23,300			184,000
Hardware Costs								
Multiplexer	MCS MUX	8,000		MCS MUX	8,000		MCS MUX	8,000
Line Adapter	MCS {2} MON {2}	7,000		MCS {2} MON {2}	7,000		MCS {2} MON {2}	7,000
Modem	MCS {2} MON {2}	8,000		MCS {2} MON {2}	8,000		MCS {2} MON {2}	8,000
Software Costs								
MCS Comm Driver	MON ULS	18,000			18,000			18,000
MON Comm Driver		9,000			9,000			9,000
Total Cost		$110,800			$114,800			$746,000
Risk	Lowest - high line availability; low error rate.			Medium - higher error rate; trunk availability.			Medium - higher error rate; trunk availability.	
Flexibility	Good - need backup via dialup for real time.			Limited - must place WATS calls; subject to busy trunks. No monitor storage.			Limited - must place calls subject to busy trunk lines. No monitor storage.	

TABLE 3-1 (1 of 3) COMMUNICATION LINK ANALYSIS: HAWAII AND MAINE

	Store and Forward Operation				
	Shared Dedicated	WATS		Dialup	
Line Costs					
Haw/Mugu	$ 0	Dialup	$23,200		$23,200
Ma/Mugu	$ 0	Measured	10,600		9,300
Hardware Costs					
Multiplexer		MCS MUX	8,000	MCS MUX	8,000
Line Adapter	$13,500 to $51,000	MCS {1} MCS {2}	4,500	MCS {1} MON {2} Dialer {1}	5,500
Modem	{See shared NAG}	MCS {1} MON {2}	6,000	MCS {1} MON {2}	6,000
Software Costs					
MCS Comm Driver	$24,000 to $54,000		18,000		18,000
MON Comm Driver	{See shared NAG}		9,000		9,000
Total Cost	$58,000 to $75,000		$79,300		$79,000
Risk	Medium {see shared NAG.}	Low - higher error rate.		Low - higher error rate.	
Flexibility	Poor {see shared NAG.}	Limited - must place WATS calls; subject to busy trunks and poor quality.		Limited - must place calls subject to busy trunk lines and poor quality.	

TABLE 3-1 (2 of 3) COMMUNICATION LINK ANALYSIS: HAWAII AND MAINE (Cont.)

3

Shared NAG Lines	A NAG/GPS Channel or Tape Interface	B NAG/GPS Comm. Interface MCS/ULS	C NAG/ULS	D Line Multiplexed
GPS HARDWARE	MCS/360 IF $25,000 MON/NAG Remote IF {2} 30,000	MCS MUX $ 8,000 LineAdapters {3} 4,500 2400BPS Modems {4} 8,000	Line Adapters {3} $ 4,500 2400BPS Modems {4} 8,000	MCS MUX $ 8,000 LineAdapters {4} 7,000 4800BPS Modems {4} {Split-Stream} 22,600
GPS SOFTWARE	MCS/360 $ 9,000 MON/NAG Remote 9,000	MCS/360 Comm 18,000* MON/360 Comm 9,000* MCS/ULS Comm 9,000	MCS/360 Comm 18,000* MON/360 Comm 9,000*	MCS/ULS Comm 9,000 MCS/MON Comm 9,000 MON/MCS Comm 9,000
		*May be less depending upon use of existing software		
NAG HARDWARE	MCS/360 IF 2,000	Line Adapter {1} 2,500	Line Adapter {2} 5,000	Replace NAG Modems with GPS Split-Stream modems.
NAG SOFTWARE	MCS/360 3,000 MON/NAG Remote 3,000	MON/360 Message Switch 18,000	MON/360 Message Switch 18,000	None
TOTAL COST	$85,000	$77,000	$62,500	$64,800
FLEXIBILITY	Schedule down time for 360, Comm line, & NAG remote. Schedule MCS/MON Comm & NAG Comm. Comm defined by NAG Pt To Pt or multidrop network.	Schedule down time for 360 & Comm line. Schedule MCS/MON Comm & NAG Comm. Comm defined by NAG multidrop network.	Schedule down time for 360 & Comm line. Schedule MCS/MON, MCS/ULS, & NAG Comm. Comm defined by NAG multidrop network.	Schedule down time for Comm line including voice & MINN/DC drop usage. Must share modems independent choice of message & character formats. Must schedule multidrop communication.
RISK	Line availability. NAG must xmit GPS data dependent upon NAG system development.	Line availability. NAG must xmit GPS data dependent upon NAG system development.	Line availability. NAG must xmit GPS data dependent upon NAG system development.	Line availability. May be difficult to schedule multidrop network.

TABLE 3-1 (3 of 3) COMMUNICATION LINK ANALYSIS: HAWAII AND MAINE (Cont.)

PHILCO
Philco-Ford Corporation
Western Development Laboratories Division

MCS/MON-ULS	Dedicated Voice Grade	Dedicated Low Speed	Dialup Store and Forward Phase I	Dialup Store and Forward Phase II	Dialup Store and Forward Phase III	Dialup Real Time Phase I	Dialup Real Time Phase II	Dialup Real Time Phase III
Mugu/Elm	$43,200*	$46,600	$40,600	$53,200	$92,900	$328,500	$525,600	$525,600

Dedicated: The dedicated voice grade line cost is via an RCA satellite link between Elmandorf, Alaska and Pt. Reyes, California with a ground line to Pt. Mugu, California.

Other dedicated voice grade lines are available via combinations of submarine cable and microwave. These lines run through West Sweetgrass, Montana and are about 50% more expensive than the satellite link.

The dedicated low speed line is available via Seattle, Washington; however 150 BPS is too low a rate for transferring upload data. As a result, low speed lines should not be used to communicate with the ULS.

Dialup: The dialup lines will vary with each call and may be via combinations of satellite, submarine cable, and microwave, etc.

Dialup S and F is based on one monitor call per hour plus 30, 90, and 135 minutes of upload for Phases I, II and III respectively. Dialup RT is based on satellite view times of 15 hours/day in Phase I and 24 hours/day in Phases II and III.

WATS: WATS service is not available to Alaska.

Comments: Availability is continuous with dedicated lines; however a backup system of dialup lines should be included.

Reliability is best on the dedicated satellite link.

*Circuits on the satellite link are still available, but it must be ordered as soon as possible to insure availability for this program.

TABLE 3-2 COMMUNICATION LINK ANALYSIS: ELMENDORF

MCS/RCF	Dedicated Voice Grade	Dedicated Low Speed	Shared NAG WATS All Phases	WATS Phase I	WATS Phase II	WATS Phase III	Dialup Phase I	Dialup Phase II	Dialup Phase III
Mugu/Vir	$29,500	$17,400	$0	$3,780	$3,780	$7,700	$1,440	$2,880	$7,900
	Mag. Tape $ 4,160								

Communication Requirement: 3.7M, 8.3M, and 22.2M bits of information every 7 days for Phases I, II, and III respectively.

Dedicated Lines: Both voice grade and low speed (150 BPS) are quite costly for the amount of data and frequency of transmission.

The 150 BPS low speed line would require 7, 16, and 42 hours of continuous communication each week. This lengthy communication would place an unreasonable requirement on the RCF and is, therefore, not considered a good approach.

WATS: The measured WATS rates of $315 per month for the first 10 hours and $23.70 per month for each additional hour were used in this analysis. Calls of 1, 2, and 5.5 hours per week for Phases I, II, and III respectively were used in the computation. These durations were based upon an effective throughput of 1200 BPS via Bell 201A type or equivalent modems.

There is a NAG WATS presently in use. It may be possible to share this WATS resulting in no cost to GPS.

Dialup: Dialup rates are based upon 1, 2, and 5.5 hours of communication every week for Phases I, II, and III respectively. The calls were computed using prime time rates.

Mag. Tape: Magnetic Tape service is based upon transporting a magnetic tape to and from the RCF each week. The tape will be transported by AIRBORNE with an intermediate carrier picking up and delivering the tapes to and from the MCS and RCF. The cost is $40 per tape transfer with two transfers required per week. Magnetic Tape carrier service cannot guarantee better than 3 days per trip due to handling by an intermediate carrier at each end.

TABLE 3-3 COMMUNICATION LINK ANALYSIS:
VIRGINIA

Telecommunications Equipment

A. Dedicated Low Speed - The dedicated low speed lines considered in this analysis are capable of providing 150 BPS, full duplex transmission on a 2-wire circuit. The data processing equipment at each end would interface to the modems via asynchronous communication adapters. The modems for this application should be Bell 103 type or equivalent. Table 3-4 summarizes low speed costs.

B. WATS or Dial-Up - Communication on WATS and dial-up lines is usually at 2000 BPS, half duplex, on the 2-wire circuit. Recent modem developments have made it possible to communicate at up to 4800 BPS on dial-up circuits. A Bell 201A or equivalent modem can communicate at 2000 BPS while a Bell 208B or equivalent modem can communicate at 4800 BPS. In each case, the modem can be capable of auto-answer or auto-dial. As shown in figure 1, the auto-dial can be initiated from either end of the link with a corresponding auto-answer modem at the opposite end of the link. The data processing equipment will interface with the modems via synchronous communications adapters which have auto-answer capability. An interface to a Bell 801 A or C auto-calling unit must also be provided for auto-dial lines. Table 3-5 and 6 summarize dial up and WATS line costs.

C. Dedicated Voice Grade - The dedicated voice grade lines are capable of up to 9600 BPS, full duplex, transmission on 4-wire unconditioned circuits. Manually equalized modems can be used for point-to-point circuits where the path does not vary (no dial-up). In many instances it may be desirable to back up the dedicated line operation with a pair of dial-up lines. In this case, it is necessary to add a Bell D33 dial-up arrangement or its equivalent. The modems (Bell 201C or 208 or equivalent) must have capability to be switched to the backup state. In this state, an operator will manually place two calls to the other end of the link. The data processing equipment will interface with the modems via synchronous communication adapters.

D. NAG Shared Lines - Dedicated voice grade lines can be shared by two independent users. This is made possible by incorporating either line multiplexers or split stream modems into the system. Figure 1 shows a split stream modem configuration. Newly developed modems (Bell 209 or equivalent) enable communication at 9600 BPS, full duplex, on unconditioned circuits. These modems have automatic adaptive equalizers and provide for configurations consisting of 2400, 4800, 7200, and 9600 bit streams. These modems can also be configured with dial-up backup circuits as described previously. When dial-up backup circuits are used, the modems will be degraded to 4800 BPS operation. In all cases, the data processing equipment will interface with the split stream modems via synchronous communications adapters.

LOW SPEED COSTS

Link	Full Duplex Cost/Month	Service Terminal	Monthly Total	Annual Total
Mugu - Hawaii	$3,420	$35	$3,455	$41,500
Mugu - Elm., Alaska	3,850	35	3,885	46,600
Mugu - Maine	1,573	35	1,608	19,300
Mugu - Virginia	1,419	35	1,454	17,400

VOICE GRADE COSTS

Link	Full Duplex Cost/Month	Service Terminal	Monthly Total	Annual Total
Mugu - Hawaii	$7,200	$100	$7,300	$87,600
Mugu - Elm., Alaska	3,500	100	3,600	43,200
Mugu - Maine	2,690	100	2,790	33,500
Mugu - Virginia	2,360	100	2,460	29,500

TABLE 3-4 DEDICATED LINE COSTS FOR LOW-SPEED AND VOICE GRADE

Hawaii	7:00 a.m. - 5:00 p.m. $3.10/1.00	5:00 p.m. - 7:00 a.m. $2.25/.75		
Alaska	7:00 a.m. - 5:00 p.m. $4.10/1.35	5:00 p.m. - 7:00 p.m. $3.10/1.00	7:00 p.m. - Mid. $2.05/.65	Mid - 7:00 a.m. $1.50/.50
Virginia	8:00 a.m. - 5:00 p.m. $1.45/.46	5:00 p.m. - 11:00 p.m. $.85/.25	11:00pm - 8:00 am $.31/.20 *	
Conus 1000 mi.	8:00 a.m. - 5:00 p.m. $1.15/.35	5:00 p.m. - 11:00 p.m. $.65/.20	11:00pm - 8:00 am $.20/.15 *	
Conus 2000 mi.	8:00 a.m. - 5:00 p.m. $1.35/.42	5:00 p.m. - 11:00 p.m. $.75/.25	11:00pm - 8:00 am $.25/.20 *	
Conus 3000 mi.	8:00 a.m. - 5:00 p.m. $1.45/.46	5:00 p.m. - 11:00 p.m. $.85/.25	11:00pm - 8:00 am $.31/.20 *	
American Samoa	Mon. - Sat. $8.00/2.65	Sun. $6.50/2.15		
Guam	Mon. - Sat. $9.00/3.00	Sun. $6.75/2.25		
Seychelles Islands	Person to Person Only $15.00/5.00			

*These rates are for first 1 minute and additional minute {1st min./add'l. min.}.
All others are for first 3 minutes and additional minute {1st 3 min./add'l. min.}.

TABLE 3-5 DIALUP LINE COSTS FROM PT. MUGU

Full Time WATS:		Cost/Month	Cost/Year
Mugu to Virginia	Band 5	$1,885	$22,600
Mugu to Conus (1000 mi.)	Band 1	1,070	12,800
Mugu to Conus (2000 mi.)	Band 4	1,785	21,400
Mugu to Conus (3000 Mi.)	Band 6	1,940	22,600

Measured WATS:		10 Hour Cost/Mo.	Add'l Cost/ Hour/Month
Mugu to Virginia	Band 5	$ 315	$23.70
Mugu to Conus (1000 mi.)	Band 1	215	16.10
Mugu to Conus (2000 mi.)	Band 4	305	22.80
Mugu to Conus (3000 mi.)	Band 6	320	24.10

WATS rates for any numbered band includes service to all lower numbered bands. Therefore, Band 6 provides service to all of Conus.

There is no WATS service to Hawaii or Alaska.

Measured WATS provides 10 hours of service per month with an additional charge for each hour per month exceeding 10 hours.

TABLE 3-6 WATS LINE COSTS

DIALUP LINE COST ANALYSIS

This analysis consists of a detailed examination of dialup costs for Phases I and III. Assumptions for each phase are listed (Tables 3-7 and 3-8). In each case, raw data quantities are based upon worse case time intervals during the 24 hour time period. In other words, the data stored for a particular time interval is calculated after determining the maximum quantity of satellite view hours for that interval during the day. The satellite view hours were determined from analysis of the view time listings for the satellite configurations. Compressed data totals were determined by reducing the tracking data to one sample per 15 minutes while maintaining the same status data as in the raw data totals.

Annual dialup line costs were determined by statistically weighing the toll charges across the 24 hour day according to the time intervals. As an example, the costs for an interval of one hour were based upon an average cost for the first three minutes and additional minutes determined by weighing the rate of each toll period by the number of calls in each toll period. Special rates for weekends were only included in the weighing of the Guam and Samoa rates. In all cases, the minimum charges for a call are based upon the telephone company's three minute minimum per call (Table 3-9).

AT&T will support data transmission on dialup lines in CONUS, Alaska, and Hawaii under Tariff 263. AT&T will not support dialup service to Guam, Samoa, Seychelles Islands or other internation lines. Transmission to international areas is possible by using modems from vendors other than AT&T. The variation in dialup path characteristics may cause variation in response times for each call.

Figures 3-2 through 3-11 summarize graphically the Phase I and III annual telecommunications line costs for ELM, Hawaii, Maine, CONUS, and Non-CONUS monitor stations, and ELM monitor to upload station.

The following conclusions can be made from the dialup cost analysis:

- The dialup minimum of 3 minutes per call eliminates the value of data compression for Phase I with one hour transmission intervals. Raw data can be transmitted within three minutes during Phase I.
- Phase I data compression for most intervals will reduce the line costs to the minimum 3 minute call.
- Data Compression provides a significant cost reduction for Phase III. Dialup transmission of raw data in Phase III is very costly.
- Line costs can be reduced significantly by increasing the interval between transmissions to 4 hours or more.

- Dialup line to an upload station is expensive as depicted in the ELM ULS/MON plots (Fig. 3-10 and 3-11). Dialup lines have less reliability and availability than dedicated lines. Availability of 1 hour or less is important for the upload link.

- The analysis was based upon 1280 BPS throughput using 2000 BPS modems. This throughput could be doubled by using newly developed 4800 BPS modems.

TABLE 3-7

PHASE I ASSUMPTIONS

1. Tracking: 168 bits/sample; 1 sample/15 seconds; 40.32K bits/satellite hour

2. Status & Meteor: 17.9K bits/operational hour

3. Upload: 225K bits/satellite/day; 900K bits/day; comm time = 12 minutes call = 30 minutes

4. RCF Data: Based upon raw data from 4 monitor stations every 7 days; also based on compressed (1/60) tracking data and raw status data

5. Dial-up Line Rate: Based upon 2000 BPS modems with 1600 BPS throughput with 20% degradation for possible ANSI control overhead resulting in 1280 BPS or 76.8K bits/minute throughput

	UNITS	MUGU	ELM	HAW	MAINE
Satellite Hours	Hours	30.54	35.43	30.1	31.85
Tracking Data/Day	Bits	1.23M	1.43	1.21M	1.28M
Operational Hours	Hours	13.87	15.05	14.1	16.53
Status and Met. Data/Day	Bits	.248M	.269M	.252M	.296M
Total Monitor Data/Day	Bits	1.478M	1.699M	1.462M	1.576M
RCF Data/Week - Raw	Bits	10.346M	11.893M	10.234M	11.032M
1/60 Compressed Tracking Data/Day	Bits	.02M	.024M	.02M	.021M
Total Compressed Monitor Data/Day	Bits	.268M	.293M	.272M	.317M
Total Compressed Mon Data/Week	Bits	1.876M	2.05M	1.9M	2.22M

RCF: Data/Week to RCF .7M Bits

Data/Week from RCF 3M Bits

Duration of Call 1 hour/week

TABLE 3-8

PHASE III ASSUMPTIONS

1. Tracking: Same as Phase I
2. Status and Met.: 32.473K bits/operational hour
3. Upload: 225K bits/satellite/day; 5.4M bits/day; comm time = 71 minutes; three 45 minute calls/day include 24 minutes of data transmission each
4. RCF Data: Same as Phase I
5. Dial-up Line Rate: Same as Phase I

	UNITS	MUGU	ELM	HAW	MAINE
Satellite Hours	Hours	184.55	213.03	184.1	194.6
Tracking Data/Day	Bits	7.44M	8.59M	7.42M	7.85M
Operational Hours	Hours	24	24	24	24
Status and Met Data/Day	Bits	.779M	.779M	.779M	.779M
Total Monitor Data/Day	Bits	8.219M	9.369M	8.199M	8.629M
RCF Data/Week - Raw	Bits	57.533M	65.583M	57.393M	60.403M
1/60 Compressed Tracking Data/Day	Bits	.124M	.143M	.124M	.131M
Total Compressed Monitor Data/Day	Bits	.903M	.922M	.903M	.910M
Total Compressed Monitor Data/Week	Bits	6.321M	6.454M	6.321M	6.370M

RCF: Data/Week to RCF (est) 4.2M Bits

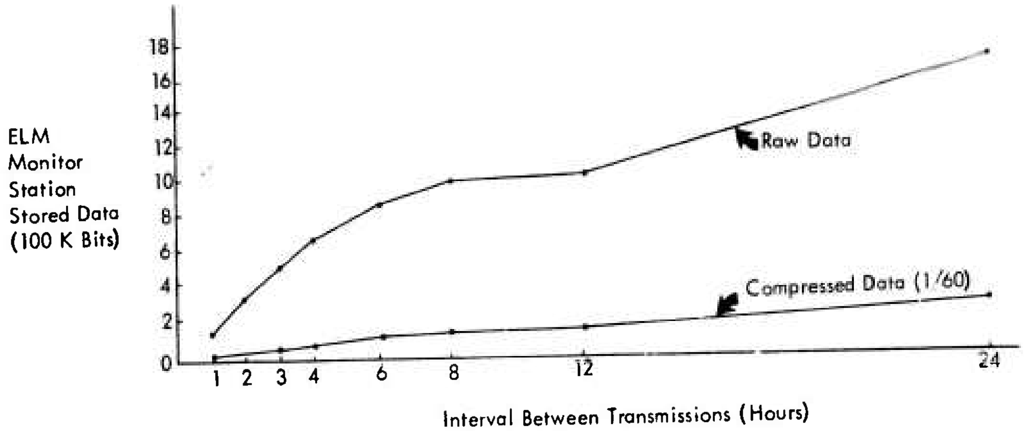
Data/Week from RCF (est) 18M Bits

Duration of Call 5.5 hours/week

TABLE 3-9

WEIGHTED DIAL-UP RATES

LINK:	DURATION	CALLS PER DAY							
		24	12	8	6	4	3	2	1
Pt. Mugu - Alaska	1st 3 Min.	2.94	3.03	3.07	3.16	3.20	3.42	3.60	4.10
	Add'l 1 Min.	.99	1.00	1.00	1.04	1.05	1.12	1.18	1.35
- Hawaii	3	2.64	2.68	2.68	2.68	2.68	2.82	2.68	3.10
	1	.87	.88	.88	.88	.88	.92	.88	1.00
- Maine	3	1.06	1.06	1.04	1.01	1.12	1.21	1.15	1.45
	1	.32	.32	.32	.31	.35	.38	.36	.46
- CONUS - 1000 mi	3	.81	.81	.80	.77	.87	.94	.90	1.15
	1	.25	.25	.25	.24	.27	.29	.28	.35
- CONUS - 2000 mi	3	.97	.97	.95	.92	1.03	1.12	1.05	1.35
	1	.31	.31	.31	.29	.33	.35	.34	.42
- CONUS - 3000 mi	3	1.06	1.06	1.04	1.01	1.12	1.21	1.15	1.45
	1	.32	.32	.32	.31	.35	.38	.36	.46
- SAMOA	3	7.79	SAME FOR ALL INTERVALS						
	1	2.56							
- GUAM	3	8.68	SAME FOR ALL INTERVALS						
	1	2.90							
- Seychelles Islands	3	15.00	SAME FOR ALL INTERVALS						
		5.00							



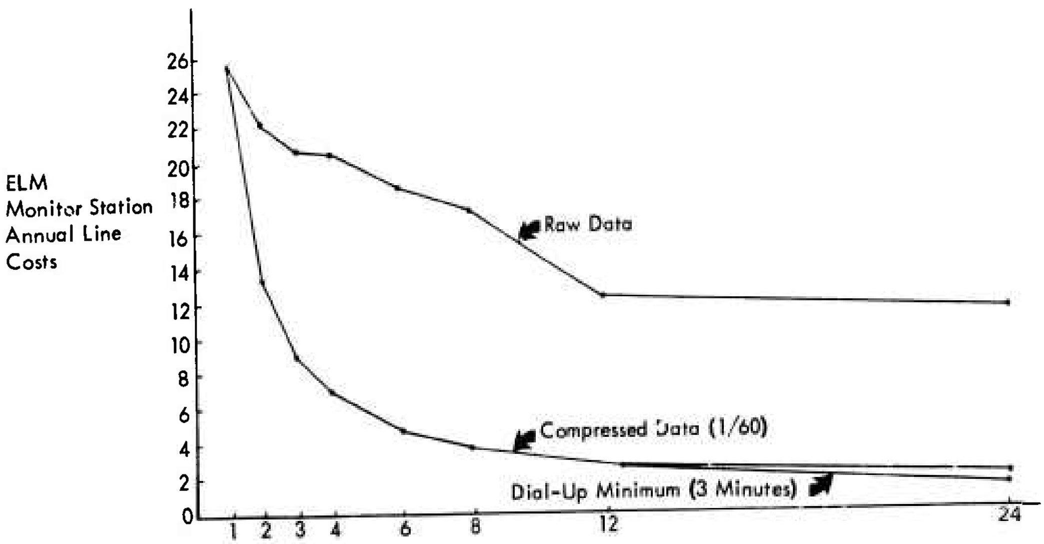


FIGURE 3-2 Telecommunications Line Cost:
ELM Phase I

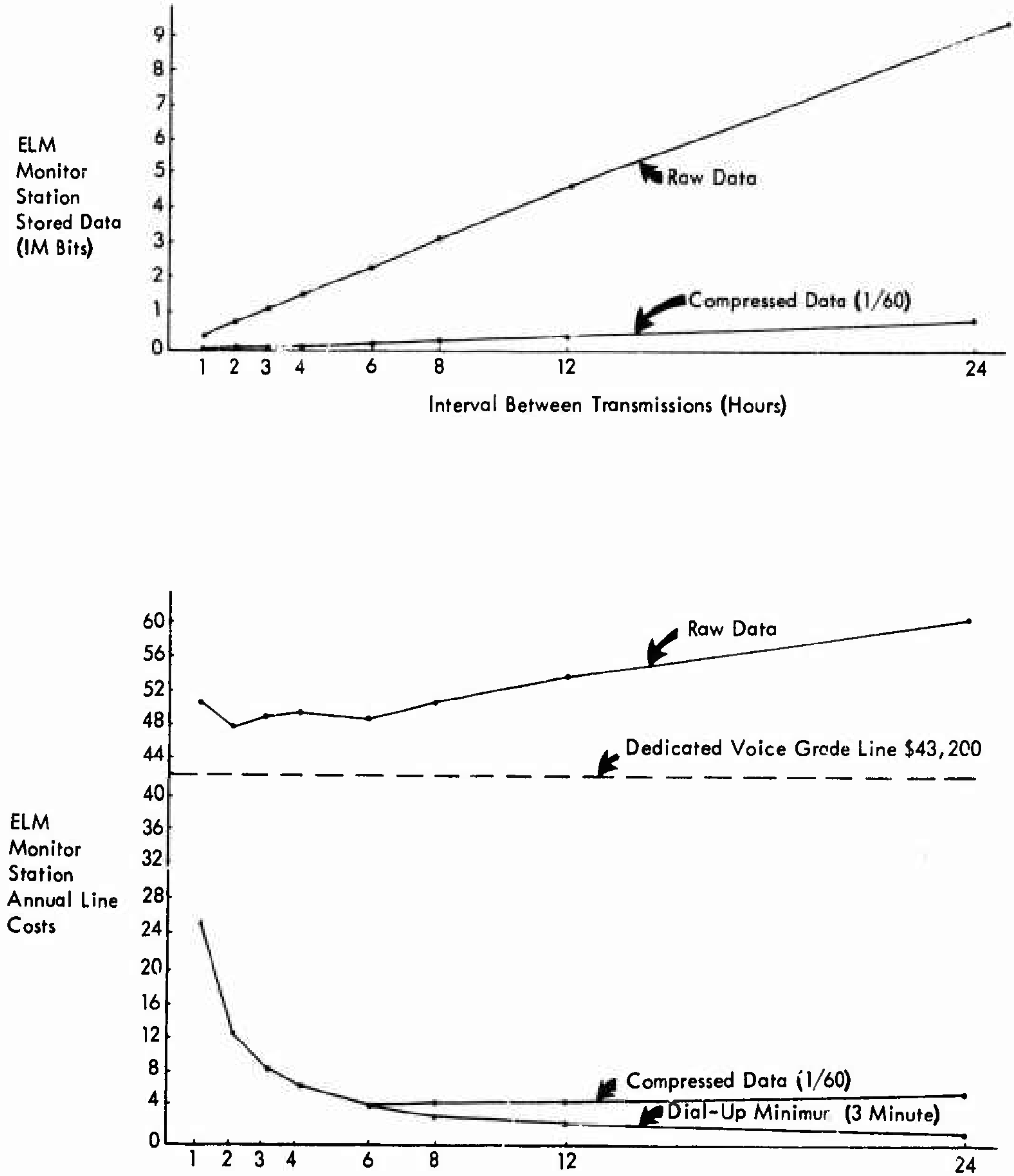


FIGURE 3-3 Telecommunications Line Cost:
ELM Phase III

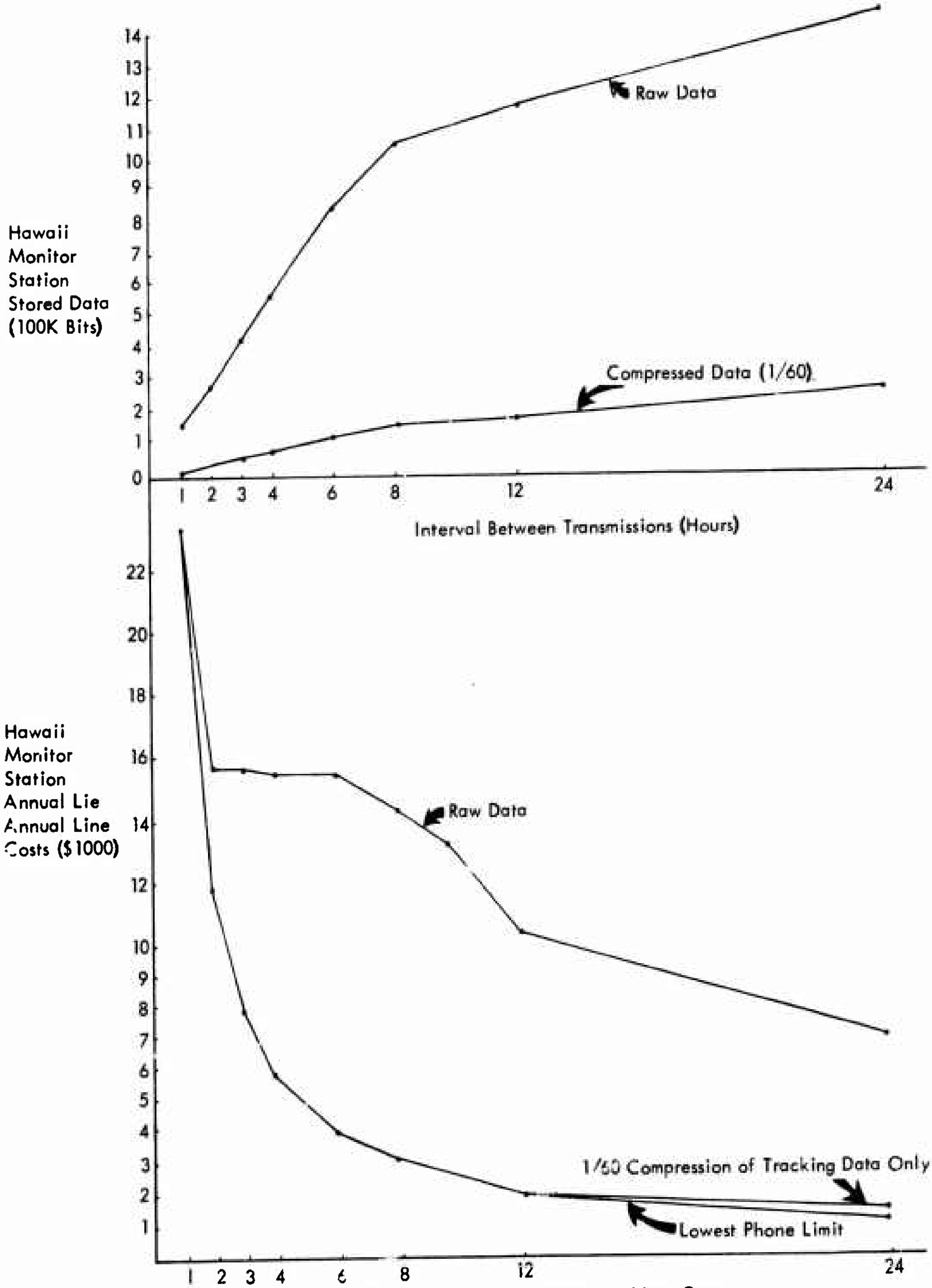


FIGURE 3-4 Telecommunications Line Cost: Hawaii Phase I

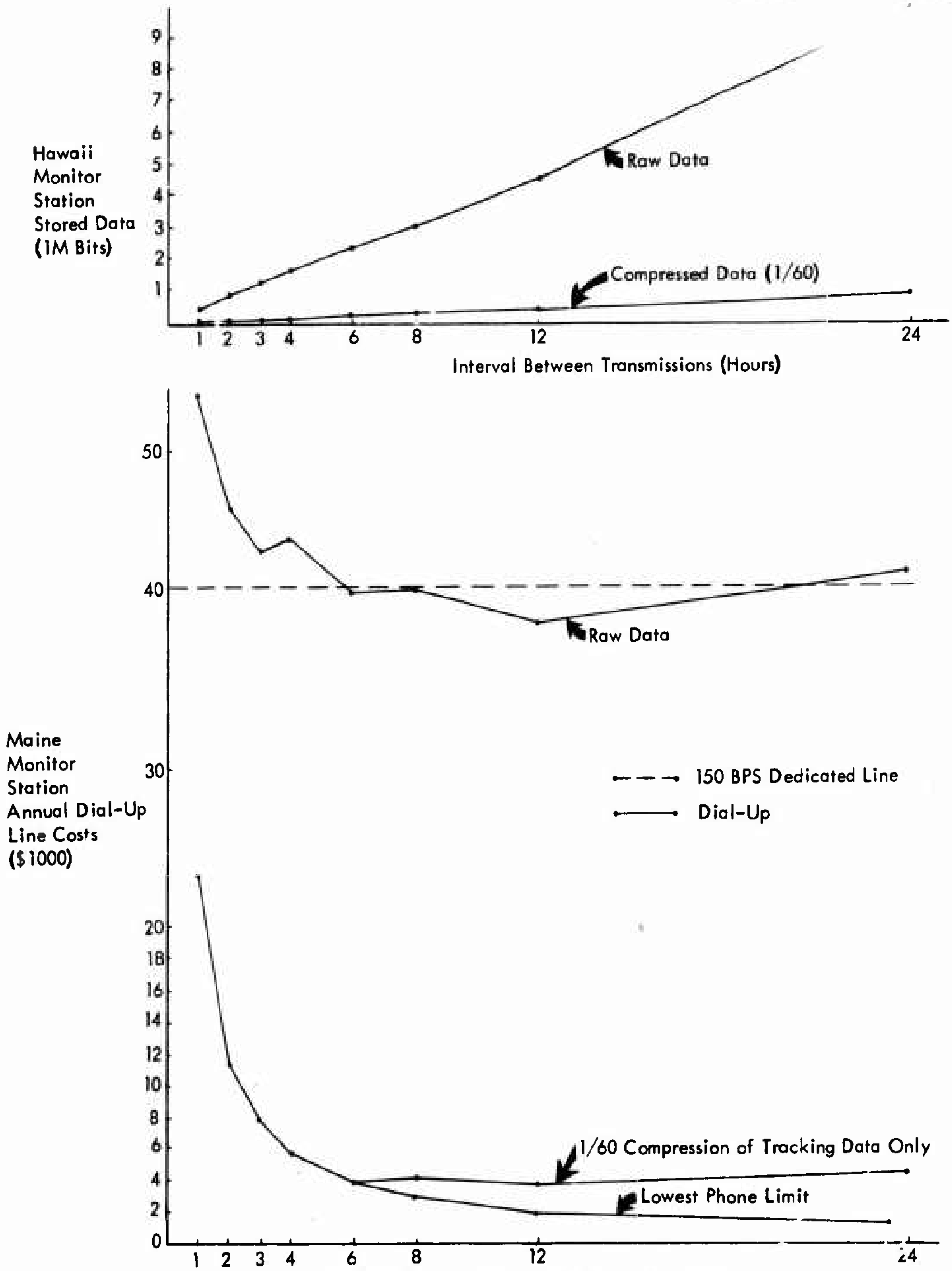


FIGURE 3-5 Telecommunications Line Cost: Hawaii Phase III

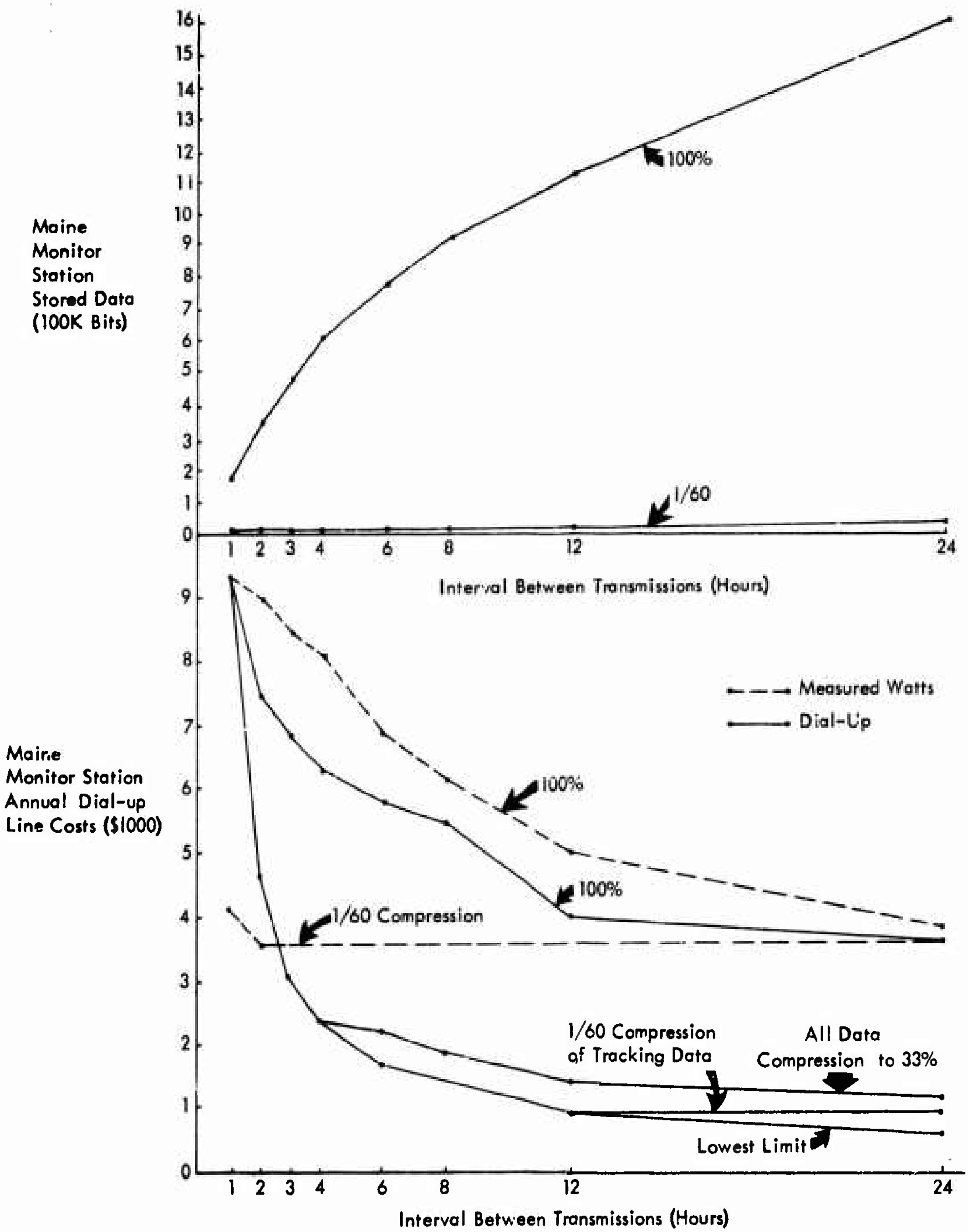


FIGURE 3-6 Telecommunications Line Cost:
Maine Phase I

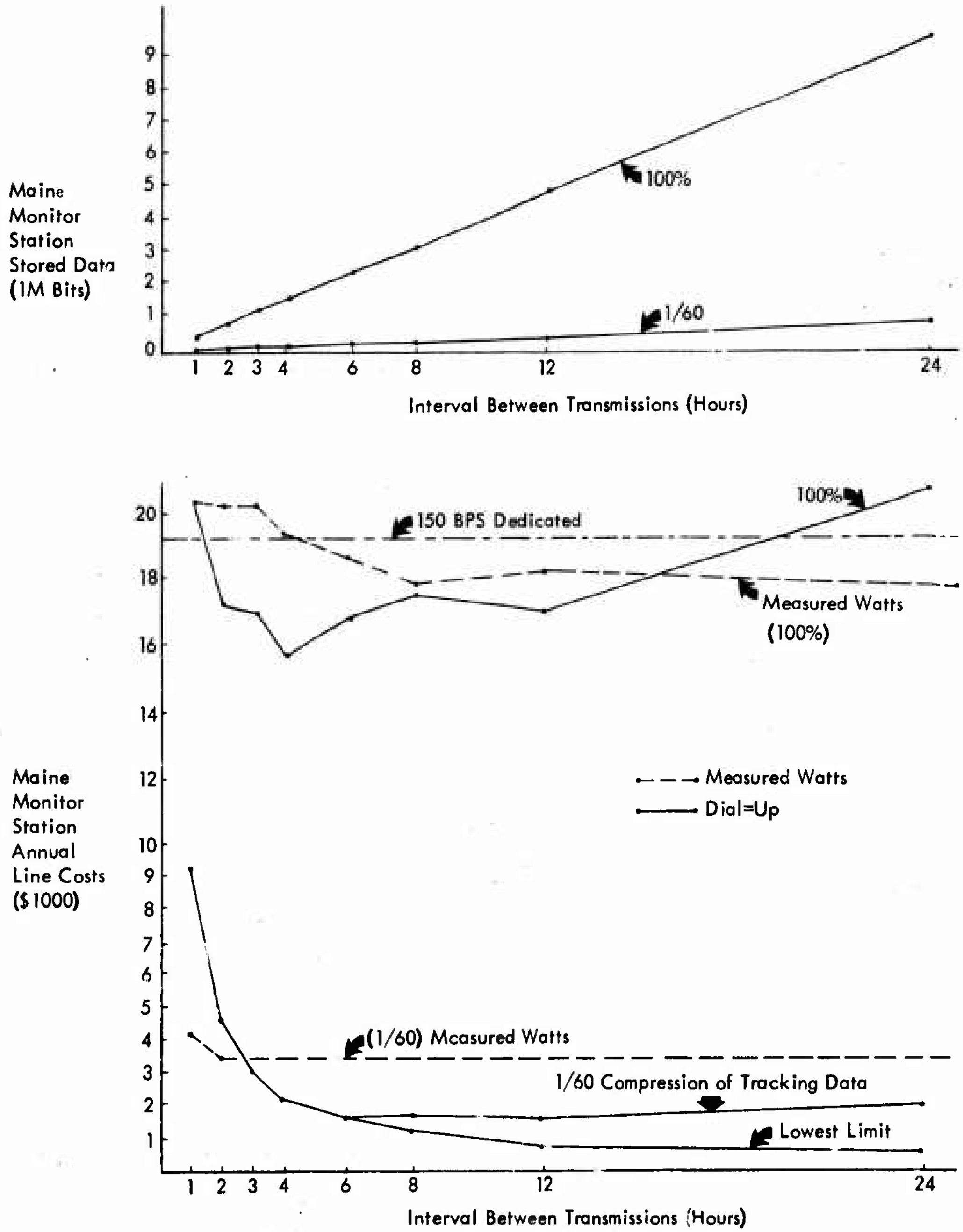


FIGURE 3-7 Telecommunications Line Costs Maine Phase III

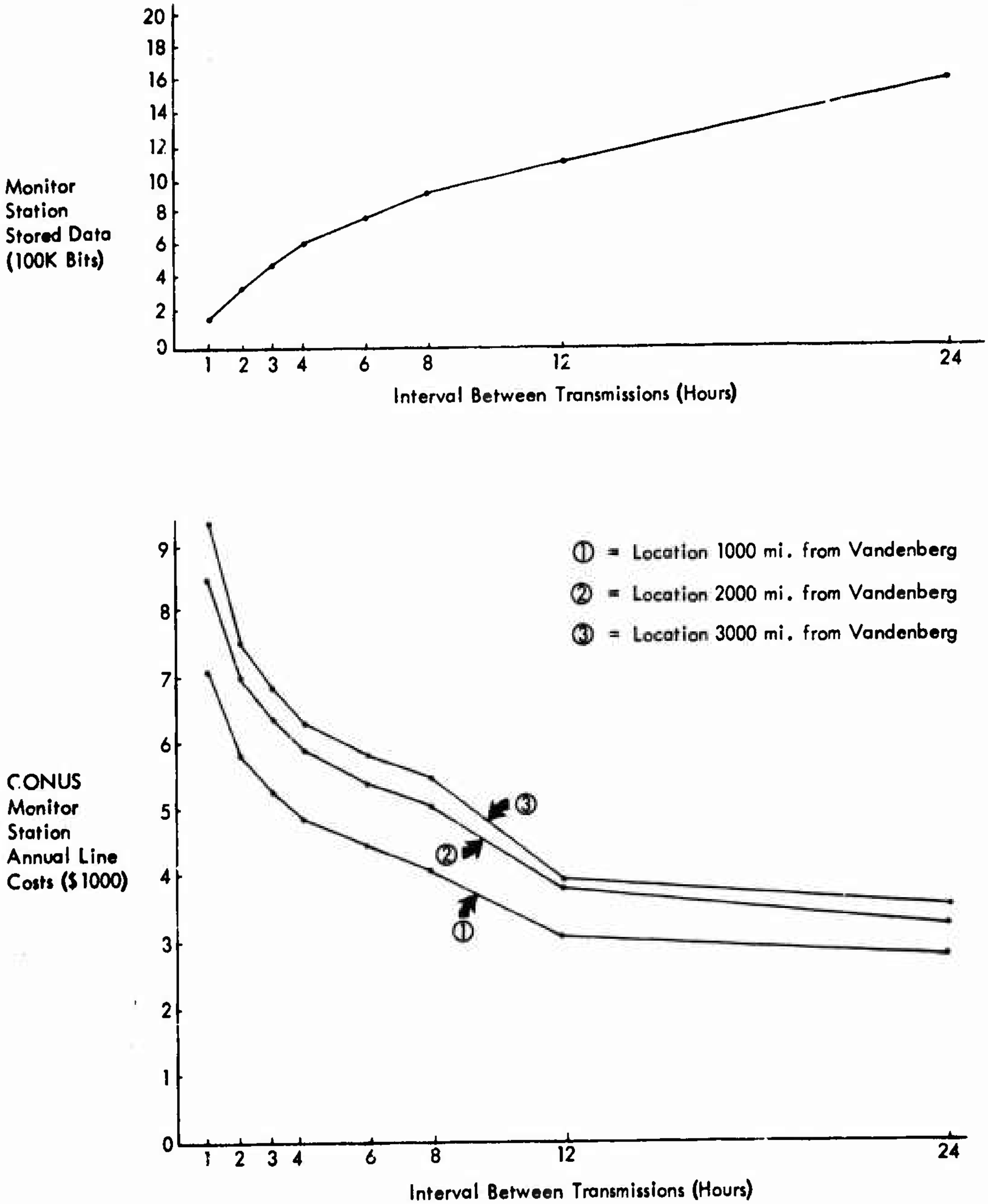


FIGURE 3-8 Telecommunication Line Cost: CONUS Phase I

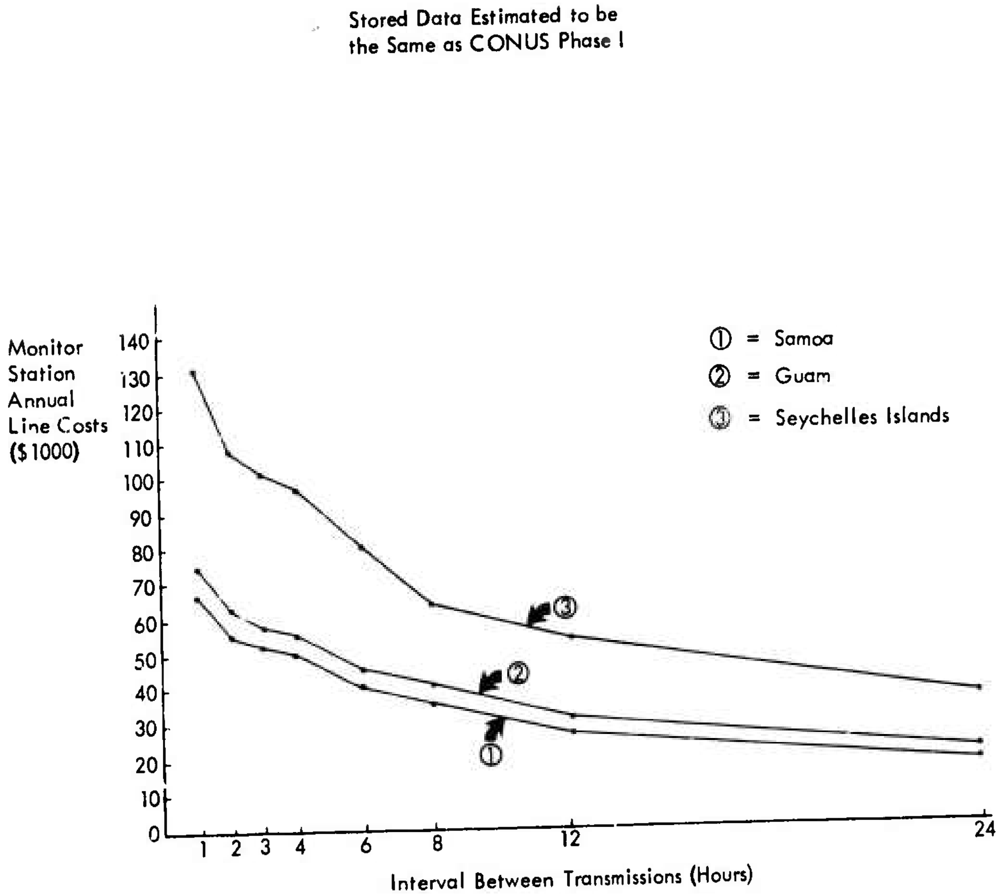


FIGURE 3-9 Telecommunication Line Cost: Non-CONUS Phase I

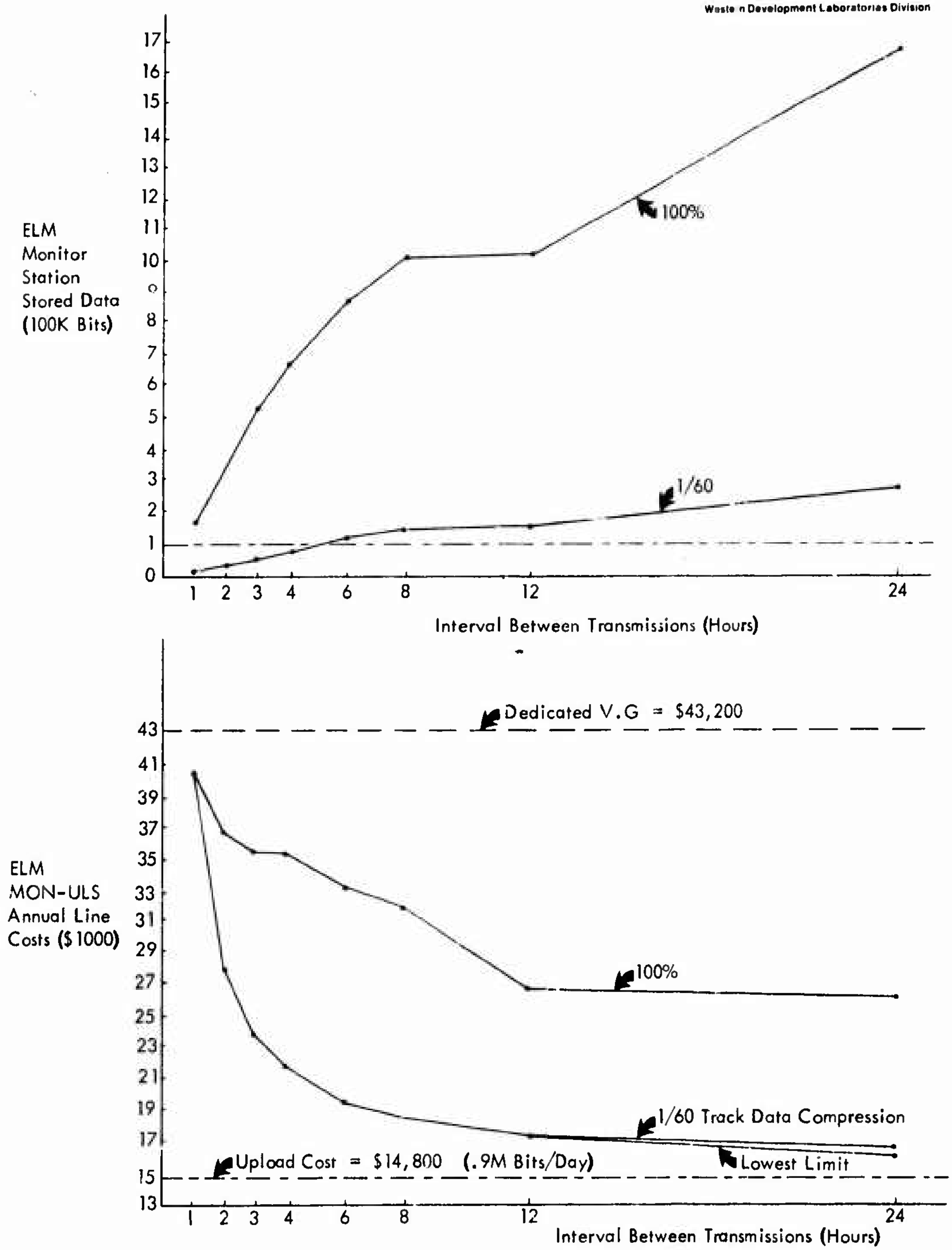


FIGURE 3-10 Telecommunication Line Cost:
ELM to Upload Station
Phase I

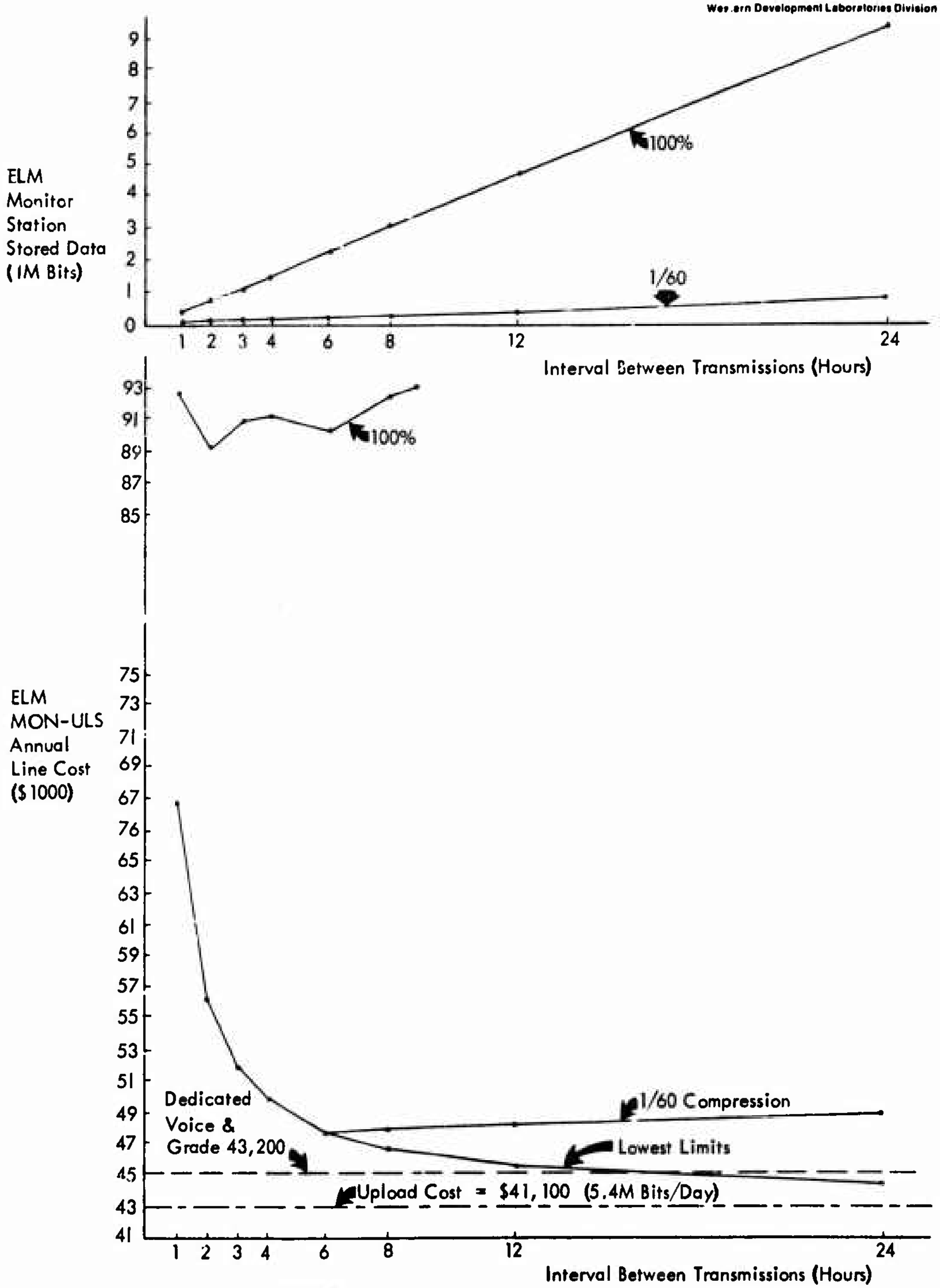


FIGURE 3-11 Telecommunication Line Cost:
ELM to Upload Station
Phase III

REPORT C 4

MCS/STC COMMUNICATIONS ANALYSIS

REPORT C 4

MCS/STC COMMUNICATIONS ANALYSIS

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LIST OF ILLUSTRATIONS

MASTER CONTROL STATION/SATELLITE TEST CENTER COMMUNICATIONS

The following options depict four alternative methods of communications between the Master Control Station and the Satellite Test Center. No attempt is made by this report to recommend any individual option but rather discuss each alternative with emphasis on the following points:

1. Communication Line Security,
3. Bird Buffer Security,
4. Personnel Requirements,
5. STC Space,
6. New Equipment Required,
7. Existing Equipment,
8. Software,
9. Cost.

OPTION I DESCRIPTION

This configuration consists of a new stand alone tape receiving station (e.g. IBM 7702) located at the STC. The mode of operation would be quite similar to that of the NAG network when data is transmitted from Pt. Magu to one of its tracking facilities.

SCF INTERFACE PROBLEMS

1. Communication Line Security.

   Data links between the MCS and the tape receiver station must be encrypted to protect the SCF's secure modem group.. See point number 8.

2. Bird Buffer Security.

   No problem as additional hardware will not interface to any of the existing equipment.

3. SCF Scheduling.

   Flexible scheduling for Upload because GPS not restrictive to one BB.

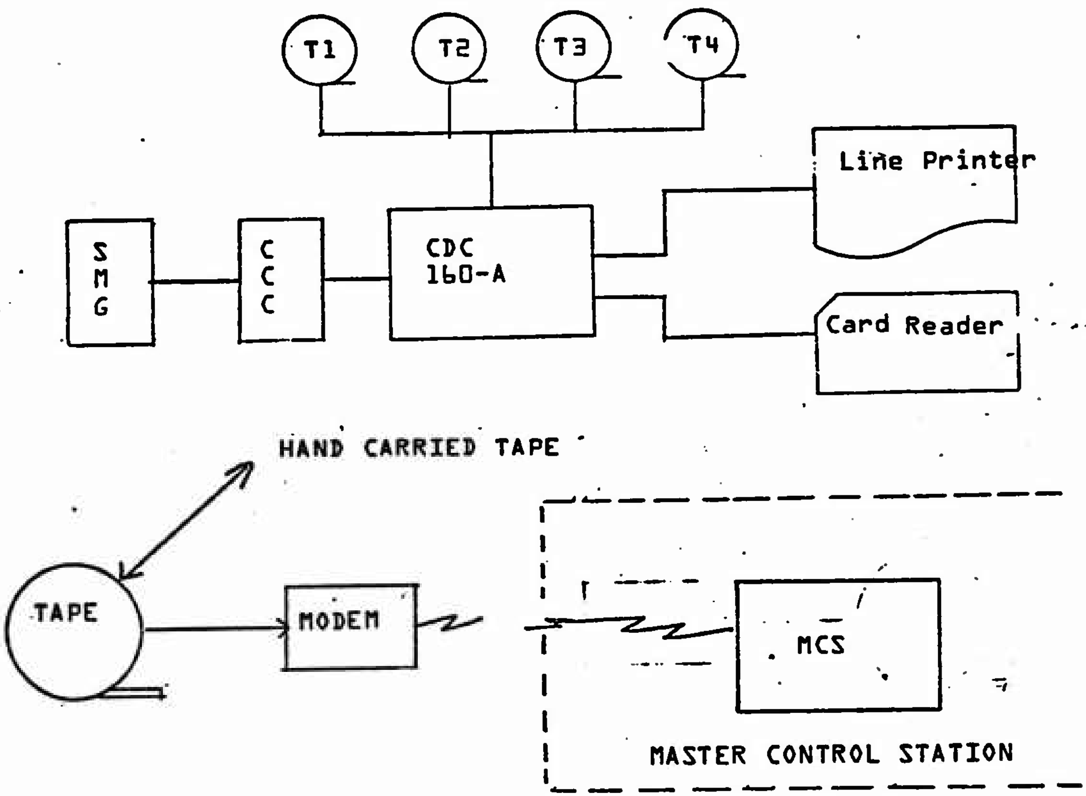

FIGURE 4-1 OPTION I - DEDICATED TAPE - TAPE SYSTEM

4. Personnel Required.

Additional operator required to monitor the tape reciever station. This does not include the operator required to transmitt the command message to the upload station.

5. STC Space.

One rack should be required to house the tape transport, reciever, and modem.

6. New Equipment Required.

1 Tape Transport
1 Receiver Station
1 Modem

7. Existing Equipment.

The reciever station might possibly be found as GFE surplus following the NAG upgrade.

8. Software.

To eliminate the first problem, it might be possible to transmitt the upload data to the SCF in some format other than that which is shipped to the RTS. This would require a package on the BB to reformat the MCS data into an SCF compatable tape.

9. Cost.

$50,000 - $80,000

OPTION II DESCRIPTION

This configuration is similar to Option I. Instead of the stand alone reciever station located at the STC there is a mini computer.

SCF INTERFACE PROBLEMS

1. Communication Line Security.

See Option I

2. Bird Buffer Security.

See Option I and Part 8 of this section.

3. SCF Scheduling.

See Option I

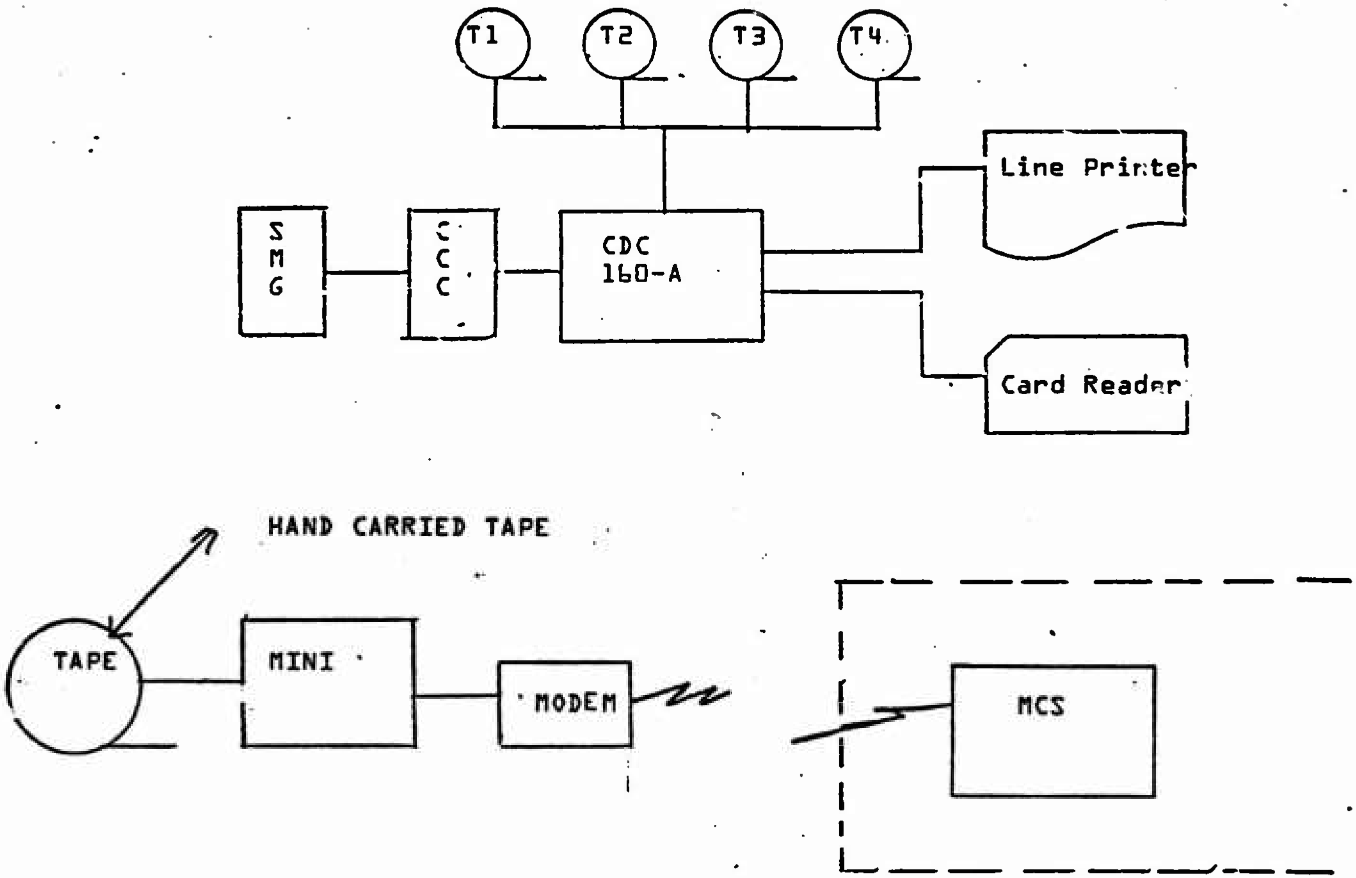

FIGURE 4-2 OPTION II-DEDICATED MINI COMPUTER

4. Personnel Required.

See Option I.

5. STC Space Required.

1 Rack.

6. New Equipment Required.

1 CPU + 8K memory
1 Tape Transport
1 Modem
1 ASR 33 Operators Console

7. Existing Equipment.

None.

8. Software.

Similar to Option I, but with this configuration the reformatting software may be done on either the BB or the mini. Software must also be provided for the mini to perform the communication function.

9. Cost.

$33,000 + software

OPTION III DESCRIPTION

This configuration consists of adding a data set controller and modem to one of the Bird Buffers located at the STC.

STC INTERFACE PROBLEMS

1. Communications Line Security.

See Option I.

2. Bird Buffer Secuity.

Probability of the SCF allowing GPS to configure any unsecure communications equipment to any on of the BB is very low.

3. Personnel Required.

BB operator only.

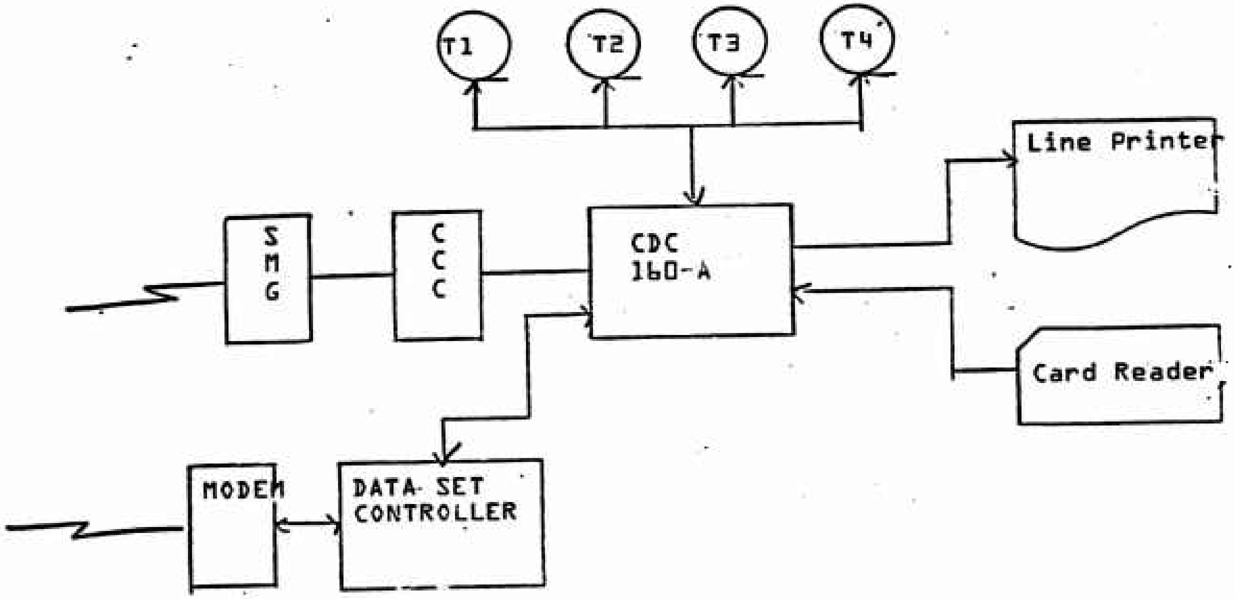

FIGURE 4-3 OPTION III - DEDICATED BB FOR MCS COMMUNICATION

4. SCF Scheduling.

GPS restricted to the utilization of a single BB to perform communication between MSC-STC. Still flexible on the transmission of Command message tape from any BB to upload station. Additional time required on BB for recieving the tape from MCS.

5. STC Space.

1/2 rack located within the STC BB area.

6. New Equipment.

1 Data Set Controller
1 Modem

7. Existing Equipment.

None.

8. Software.

Communication software with any data set controller does not exist

See Option I.

9. Cost.

$8,000 + software

OPTION IV DESCRIPTION

Configuration similar to Option III but data set controller and modem are now switchable to any of the currently utilized BB's.

1. Communication Line Security.

See Option I.

2. Bird Buffer Security.

See Option III.

3. Personnel Required.

Additional task allocated to Data Systems Controller for the switching of the Communication Equipment to any BB.

4. <u>SCF Scheduling</u>.

None other than additional transmission time must be scheduled for receipt of message from MCS.

5. <u>STC Space</u>.

2 Racks.

6. <u>New Equipment</u>.

1 Data Set Controller
1 Modem
1 Matrix Switch
1 Switching Console

7. <u>Existing Equipment</u>.

None.

8. <u>Software</u>.

See Option III.

9. <u>Cost</u>.

$20,000 + software

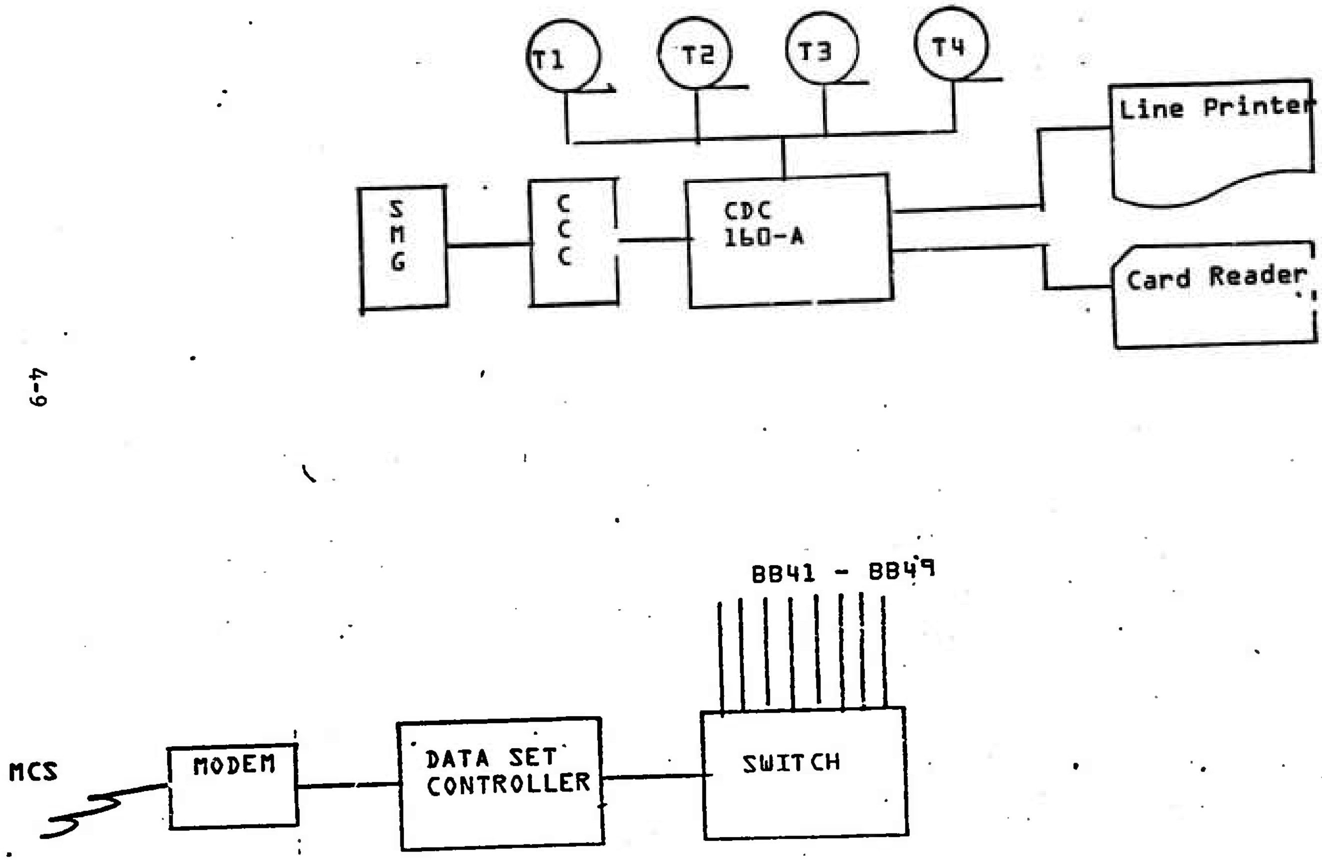

FIGURE 4-4 OPTION IV - MULTI BB SELECT

TABLE 4-1 SCF TO MCS COMMUNI[illegible]IONS SUMMARY

	OPTION I	OPTION II	OPTION III	OPTION IV
	Dedication Tape to Tape System	Mini-Tape Receive Station	Dedicated BB With Comm.	Switchable Com To Any BB
MCS/STC Comm Line Security	Potential Problem	Potential Problem	Potential Problem	Potential Problem
BB Security	No Problem	No Problem	Problem	Problem
Personnel Req.	2 Operators	2 Operators	BB Oper. Only	BB Oper. + DSC {ACES}
SCF Scheduling	Flex - Any BB	Flex - Any BB	Restricted to One BB	Flex - Any BB
STC Space	1 Rack	1 Rack	1/2 Rack	2 Racks
New Equip. Req.	1 Tape Trans 1 Recv. Station 1 Modem	1 Tape Trans 1 CPU & 8K Memory 1 Modem 1 ASR 33	1 Data Set Cont. 1 Modem	1 Data Set Cor 1 Modem 1 Matrix Switc
Existing Equip.	None - Possible GPE Surplus	None	BB Only	BB Only
Software	BB Package to Reformat Data to Negate Point One**	Mini Package to Reformat Data to Negate Point One	Same as I	Same as I
		Comm Software Required in Mini	Same as II	Same as II
Cost	$50,000 - 80,000	$30,000 + Software	$10,000 + Software	$20,000 + Software
	**Not required if MCS to SCF Data Line is Secure			

REPORT C 5

MCS DATA PROCESSING CONFIGURATION STUDY

REPORT C 5

MCS DATA PROCESSING CONFIGURATION STUDY

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LIST OF ILLUSTRATIONS

1.0 MCS CONFIGURATION TRADE

This trade addresses the general computer configuration to be employed at the MCS for Phase 1 of GPS. Specifically, the issue being considered is whether to use a single integrated processor or separate processors for on-line control functions and navigation support functions. The two candidate configurations are depicted in Figure 5-1.

2.0 FUNCTIONAL AND TECHNICAL REQUIREMENTS

The software functions to be performed on the MCS processor are as follows:

a. MCS operations and control, including analyst support

b. Two-way communications

   1. between MCS and Monitor Stations
   2. between MCS and Upload Station
   3. between MCS and the AFSCF

c. System status monitoring

d. System performance monitoring

e. Monitor station tracking data processing

f. Satellite vehicle ephemeris estimation and prediction

g. Satellite vehicle clock estimation and prediction

h. Satellite vehicle upload data file generation

3.0 ALTERNATE CONFIGURATIONS

3.1 Configuration A - Integrated Processor

As depicted in Figure 5-1, all MCS computer functions are accomplished on a single processor in configuration A. The communications and control software are resident in main memory. Communications lines and analyst CRTs are serviced, by the navigation processor (NAP), concurent with other software functions.

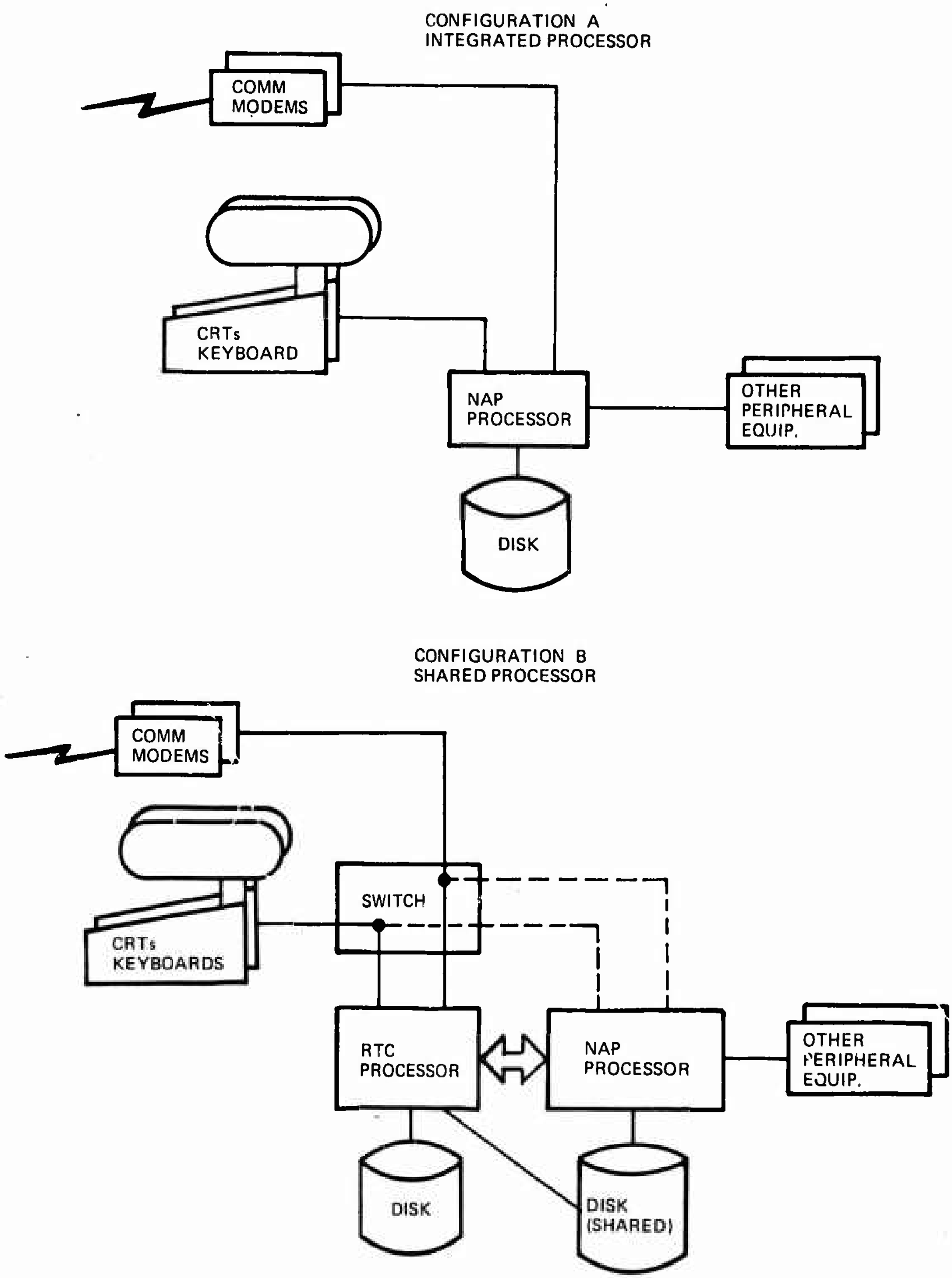

FIGURE 5-1 MCS CONFIGURATION ALTERNATIVES

3.2 Configuration B - Separate Processors

Figure 1 also depicts configuration B. During normal operations a realtime computer (RTC) services communications lines and analyst consoles. Incoming tracking data is placed directly on a disk which is shared with the NAP. MCS control software also resides in the RTC which directs the operations of the NAP.

The RTC is responsible for the following functions:

a. MCS operations and control, including analyst support

b. Two-way communications

   1. between MCS and Monitor Stations
   2. between MCS and Upload Station
   3. between MCS and AFSCF

c. System status monitoring

d. Interface with NAP and direction of NAP operations

The NAP is responsible for the following functions under direction of the RTC:

a. Interface with RTC and assist MCS operations and control

b. System performance monitoring

c. Monitor Station tracking data processing

d. Satellite vehicle ephemeris estimation and prediction

e. Satellite vehicle clock estimation and prediction

f. Satellite vehicle upload data file generation

A principle consideration for configuration B is to improve MCS availability by allowing a NAP processor failure. If such occured, system control, status monitoring, and monitor/upload station communications could still continue. However, if the two processors are connected only in a serial fashion, overall MCS availability would be reduced. Thus to allow for an RCT failure, communications lines and analyst CRTs must be switchable to the NAP, and the NAP must be capable of assuming all RTC functions.

4.0 EVALUATION CRITERIA

The following criteria is used to evaluate the two configurations:

- o availability
- o cost
- o legacy

5.0 COMPARISON OF ALTERNATIVES

5.1 Availability

There are three principle aspects to MCS availability: availability for monitor station communications and system status monitoring; availability for upload message transmission; and availability for upload message generation. Using the analysis presented in Part I, Vol. C, Systems Analysis Report Section 7.9, configuration B improves avail[illegible]r comm[illegible] and system status monitoring by 0.1%. It also improves availability for upload message transmission by about 0.5%. Both of these improvements are due to the redundancy provided for communications and analyst console support. However, no improvement is attained in availability for upload generation since NAP processing is required.

For Phase 1, the overall MCS availability requirement is 92%. For either configuration, currently available processing equipment provides MCS availability in the order of 98%, which far exceeds the 92% requirement.

5.2 Cost

The functions assumed by the RTC processor in configuration B relieve the NAP processor of about 3% of its peak loading requirements (for operations and control function and status monitor function) and about 10% of its main memory requirements (for operations and control function resident). This reduction is not sufficient to justify any reduction in NAP processor or main memory requirements. Further, if the NAP is to have the capacity to manage the system in the event of RTC failure, it must be of the same size as in configuration A. Thus configuration B involves additional hardware costs for the RTC processor, disk, peripheral switch, and computer channel interface.

For the system to function in the event of an RTC failure, all RTC software must also be developed for the NAP in configuration B, just as in A. Thus, all RTC software represents additional costs for configuration B. Further, the complexity of the control function software is increased for configuration B, involving even higher software costs.

Another consideration in configuration B software costs, is the special (tailored) system software required for shared disk use and support of the master/slave relationship between RTC and NAP processors. The following table summarizes additional cost estimates for configuration B, as percent of those for configuration A.

o <u>Approximate Hardware Costs</u>		
o RTC Processor and Memory	2.3%	
o RTC Disk	3.7	
o Peripheral Switch	0.3	
o Computer Channel Interface	1.0	
o Total Additional Hardware Cost		7.3%
o <u>Approximate Software Costs</u>		
o Operations and Control	10.8%	
o Communications Handler	4.1	
o Status and Fault Detection	8.1	
o RTC/NAP Interface	9.0	
o Total Additional Software Cost		32%

5.3 Legacy

The maximum possible increase in peak loading for Phase 2 is about 32% due to the possibility of generating upload messages for 5 satellites simultaneously instead of 4. Increase communications load due to the larger volume of tracking data does not effect peak loading of the NAP processor for either configuration.

This is because monitor communications are scheduled for times when the NAP processor is not heavily loaded. The increased load on the NAF processor for Phase 2 is absorbed by the excess computing capacity necessary for Phase 1 system development. This applies to either configuration. Thus, the configurations offer equivalent Phase 2 legacy.

6.0 CONCLUSIONS AND RECOMMENDATIONS

A summary of the trade is given in Table 5-1. Adding a realtime processor to the MCS to handle communications and status monitoring functions improves overall MCS availability by about 0.05%. Availability for communications and status monitoring support is improved by about 0.1%. However, the increase of about 7% in hardware cost and about 32% in software cost outweigh this small increase in availability. Even without the realtime processor, MCS availability is expected to far exceed Phase 1 goals. The recommended configuration for Phase 1 uses a single processor for all MCS functions.

TABLE 5-1

MCS CONFIGURATION TRADE

SUMMARY

	Configuration A	Configuration B
availability	Good o Satisfies requirements	Best o Satisfies requirements
cost	Lowest	Highest o Software up 32% o Hardware up 7.3%
Legacy	Good	Good

CONCLUSION

Configuration A (Integrated Processor) is the recommended configuration.

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MONITOR STATION DATA PROCESSING TRADE

REPORT C 6

MONITOR STATION DATA PROCESSING TRADE

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LIST OF ILLUSTRATIONS

1.0 MONITOR STATION CONFIGURATION TRADE

This trade study addresses the general processor configuration for GPS Monitor Stations (MS). Specifically, it considers whether, and how, to employ the user equipment processor in the MS configuration. The alternatives are illustraded in Figures 6-1 through 6-3.

2.0 FUNCTIONAL REQUIREMENTS

The MS processor(s) provide the following functions.

a. Receiver Interface
   1. Input time, tracking data, and downlink signal data
   2. Direct satellite acquisition

b. Communications with MCS
   1. Accept schedule from MCS
   2. Transmit tracking and status data to MCS

c. Test Equipment Interface

d. Equipment Scheduling and Control

e. Process Receiver Data
   1. Validate downlink signal data
   2. Collect tracking data

f. Perform Navigation Solution

g. Support Teletype

3.0 ALTERNATE CONFIGURATIONS

Three configurations are considered: a separate monitor processor (MP) that interfaces with the user processor (UP); a shared UP which performs both user and monitor functions; and a shared MP which interfaces with the user receiver

and performs both user and monitor functions.

3.1 Alternate A - Separate Processor

Under this alternative, a separate processor is employed for MS functions. The class A user equipment group remains intact, including the UP. A computer channel is added to interface the MP and the UP. UP software is modified to interface with, and accept controls from the separate MP. The MP also controls MS test equipment and is interfaced with a communications modem and a teletype. MP and UP functions for Alternate A are listed in Figure 6-1.

3.2 Alternate B - Shared User Processor

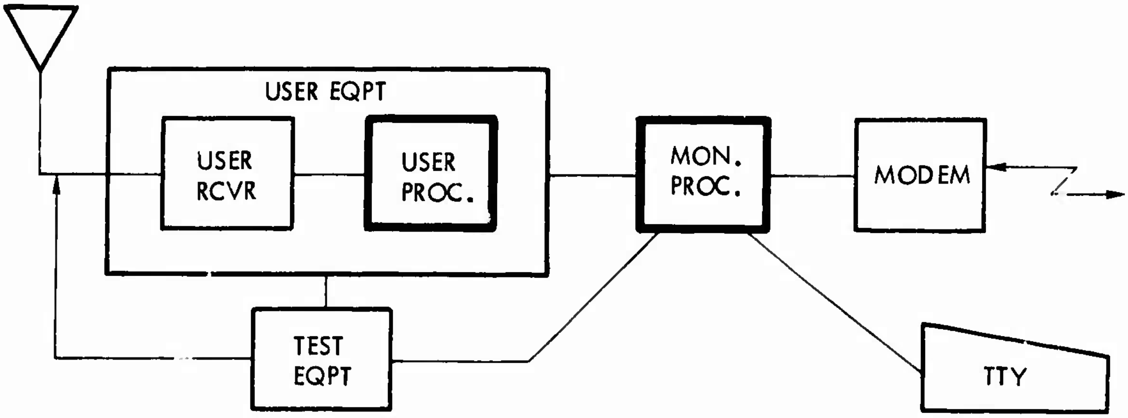
Under this alternative, all MS functions are integrated into the UP. That is, MS software is programmed and executed on the UP. UP software is modified to interface with, and accept controls from MS software which also resides in the UP. Additional hardware is added to the UP for interface with MS test equipment, communications modem, and teletype. Additional memory is also added to the UP to accommodate MS software and data buffers. All UP functions and MS processor functions are accomplished by the UP, as listed in Figure 6-2 for Alternate B.

3.3 Alternate C - Shared Monitor Processor

Under this alternative the MP is interfaced directly with the user receiver. The processor is removed from the class A user equipment group and is not used. Instead, the subset of this processor's functions required for the MS are programmed and executed on the MP. Since this subset requires a relatively large storage capacity, a small disk becomes cost effective and is employed in this configuration for software and data buffer storage. The MP is interfaced with MS test equipment, communications modem, and teletype as well as user receiver and disk. All MS processor functions are accomplished by the MP, as listed in Figure 6-3 for Alternate C.

4.0 EVALUATION CRITERIA

The MS configuration trade alternatives are evaluated with respect to the



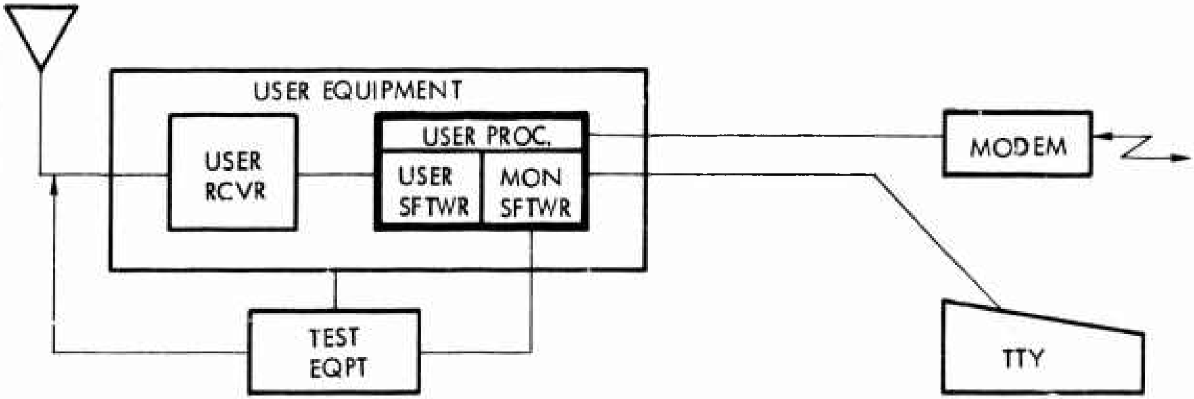
MONITOR PROCESSOR FUNCTIONS

- o Communications with MCS
- o Equipment Scheduling and Control
- o Process Receiver Data
- o Test Equipment Interface
- o Support Teletype
- o Interface with User Processor

USER PROCESSOR FUNCTIONS

- o Receiver Interface
- o Process Reveiver Data
- o Perform Navigation Solution
- o Accept Control from Monitor Processor
- o Interface with Monitor Processor

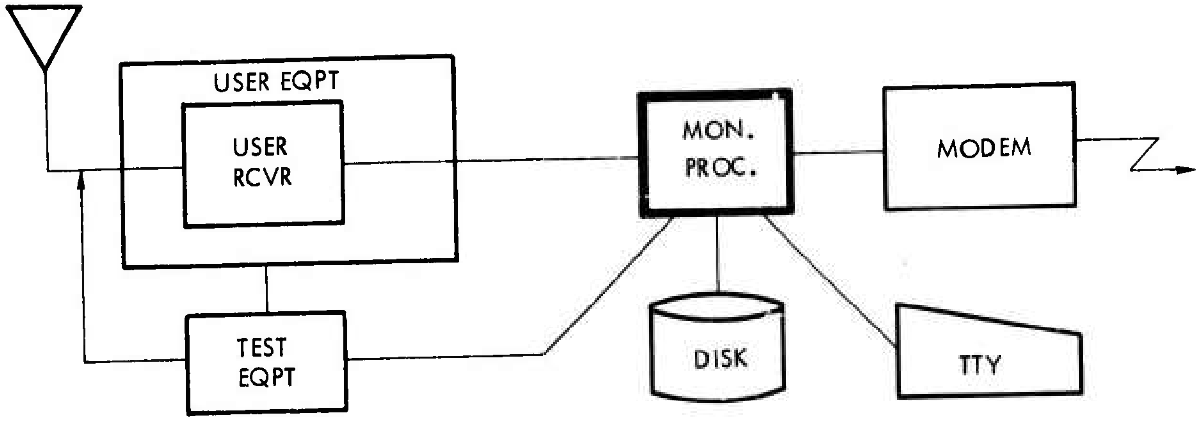
Figure 6-1 Alternate A - Separate Processors



USER PROCESSOR FUNCTIONS

- o Receiver Interface
- o Communications with MCS
- o Test Equipment Interface
- o Equipment Scheduling and Control
- o Process Receiver Data
- o Perform Navigation Solution
- o Support Teletype

Figure 6-2 Alternate B - Shared User Processor



MONITOR PROCESSOR FUNCTIONS

- o Receiver Interface
- o Communications with MCS
- o Test Equipment Interface
- o Equipment Scheduling and Control
- o Process Receiver Data
- o Perform Navigation Solution
- o Support Teletype
- o Support Disk

Figure 6-3 Alternate C - Shared Monitor Processor

following criteria.

a. cost
b. risk
c. legacy

5.0 COMPARISON OF ALTERNATIVES

The three alternate configurations are considered with respect to each of the evaluation criteria.

5.1 Cost

Relative cost estimates are given in Table 6-1. In general, alternate A has the highest hardware costs since two processors must be purchased for each MS. Alternate C has the lowest hardware cost due to the elimination of the relatively expensive, highly durable user equipment computer. The user computer is slightly more expensive in alternate B, compared to alternate A, since additional memory is required for MS software and data buffers.

Alternate A shows the lowest software cost since user equipment software functions do not have to be developed for the MP as in alternate C. Alternate B costs are estimated high since it requires, essentially, another version of user software. This is because user software must be restructured to accommodate MS functions. Alternate A can be accomplished with relatively minor modifications to user software.

The software/software integration costs arrise from integration of user and MS software in the same processor. The cost figures reflect the greater difficulty of this integration in alternate B compared to alternate C. This is because user software sub-components can be converted intact for use on the MP in alternate C. However, substantial modifications to user equipment software logic are required to interface it with MS software on the UP in alternate B.

The software/hardware integration costs arise from interfacing external equipment with the monitor computer. It is higher for alternate A because of the additional computer to computer interface required between the UP and the MP.

The total cost figures reflect Phase 1 data processing equipment and software for 4 monitor stations. Alternate C is significantly less costly for this initial implementation.

TABLE 6-1

RELATIVE COSTS* FOR PHASE I
MS DATA PROCESSING EQUIPMENT
AND SOFTWARE

	ALT A	ALT B	ALT C
Software Development	19	25	28
Software/Software Integration	-	7	4
Software/Hardware Integration	11	9	9
Total Software Cost	30	41	41
User Computer	48	52	-
Monitor Computer	22	-	22
Disk	-	-	7
Total Hardware Cost	70	52	29
Total Data Processing Cost	100	93	70

* Costs are percentages of alternate A total and consider 4 phase 1 monitor stations

5.2 Risk

The highest apparent risk factor concerns alternate B. The Phase 1 system provides a test environment in which possibly substantial modifications may be necessary to MS software and/or user equipment software. Since these two separately developed and maintained CPCI's are integrated into one processor in alternate B, any change to one may have unforeseen adverse effects on the other. This represents the risk of incurring additional software integration costs and schedule delays during Phase 1 testing. In addition, the constraints placed on the UP by MS software functions could prevent attainment of minimum UP cost goals without establishing another special class of user equipment for MS use. From these two considerations, it is concluded that the greater hardware and software flexibility of both user equipment processor and MS processor offered by alternates A and C, provide less risk than alternate B.

The comparison of alternate A and alternate C concerns the risk involved in a computer to computer interface compared to that involved in a computer to receiver interface. Modifications to user equipment software may have unforeseen adverse effects on the UP/MP interface software in the UP. However, the risk is not as great as in alternate B, since the alternate A software interface is not as extensive. On the other hand, the user receiver interface may be difficult to deal with for MS purposes. This could cause schedule delays and increased interface costs. For this reason it is concluded that there is no significant difference in risk between alternate A and alternate C.

5.3 Legacy

The major change in MS configuration for later phases is expected to be the addition of receiver capability. Adding receivers requires adding high cost UP's in both alternates A and B. Alternate B will also require additional interface hardware and software for coordinating the multiple MS processors; one in each user equipment group. Under alternate C, user receivers may be added without adding UP's.

The increased volume of tracking data in later phases may require additional

auxiliary storage capability, possibly in the form of a disk. In alternates A and B this will require additional interface hardware and software modifications. For alternate B it is not clear whether three such disks would be required per monitor station or a single shared disk would be used, even further complicating the hardware and software interfaces. Since disk storage is cost effective in Phase 1 for alternate C, at minimum the software logic has been designed to accommodate this possible increase in auxiliary storage requirements.

Because of these considerations, alternate A offers higher legacy for later phases than alternate B. However, alternate C provides significantly higher legacy than either alternate A or B.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The trade is summarized in Table 6-2. Sharing the user equipment processor for MS functions and user equipment functions involves relatively high cost, high risk and low legacy. Using a separate processor for MS functions, interfaced with the user equipment processor, eliminates the high risk factor, and increases legacy. However, it also increases costs. Removing the user equipment processor and allocating MS and user equipment functions to the monitor processor provides relatively lower costs, lower risk, and higher legacy.

The recommended configuration employs a monitor station processor, selected to be functionally/electrically compatible with the user processor, but also to satisfy MS requirements. This processor is interfaced with the user equipment receiver. The processor is removed from the user equipment group, and the required subset of its functions implemented on the monitor processor

TABLE 6-2

MS CONFIGURATION TRADE SUMMARY .

	Alternate A	Alternate B	Alternate C
COST	HIGHEST o 100% ^	HIGH o 93% ^	LOW o 70%
RISK	LOWER o UP software updates are possible risk ^	HIGH o UP/MS software updates are a continued risk o MS requirements constrain UP ^	LOWER o Receiver interface risk ^
LEGACY	LOW o More UP's required o Must add disk ^	LOWEST o More UP's required o UP coordination software o Must add disk ^	HIGH o Minimum processor and software changes required ^

ALTERNATE C IS RECOMMENDED

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REFERENCE EPHEMERIS DATA PROCESSING
COST ANALYSIS

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REPORT C 7

REFERENCE EPHEMERIS DATA PROCESSING COST ANALYSIS

LIST OF ILLUSTRATIONS

1.0 SCOPE

This report analyzes the cost impact of reference ephemeris generation, particularly the cost and flexibility differences between sizing the MCS processor to generate the reference ephemerides and sizing the MCS processor to utilize an outside service for the reference ephemeris production. The conclusions reached in this analysis show that the lease/buy decision is quite sensitive to the safety margins applied to Phase I instruction requirements. If the assumed margin of 75% were reduced to 0%, the conclusion could be reversed. The results are also sensitive to the time required to run the program. More refined estimates should be generated before commitments are made.

2.0 BASES FOR ANALYSIS

2.1 Functional Requirements

a. MCS Processing System

1. Interface to monitor stations via communication equipment to transmit schedules and commands, and to receive tracking data and status.

2. Interface to upload stations via communications equipment to transmit upload messages and commands and to receive upload verification and status.

3. Interface to the AFSCF via communication equipment to receive vehicle health data (also, possibly interface to NRL for health data for the NTS-2 spacecraft) and transmit back-up upload message.

4. Interface to operational analysts via keyboard entry display equipment to receive commands and displays system status and parameters.

5. Interface to a TBD processing system to periodically send tracking data and receive reference ephemerides and calibration of system ephemeris models.

6. Provide the data processing required to support the navigation mission using reference ephemerides, and to give adequate information about the system's performance.

7. Provide support for GPS software development and maintenance.

b. Ephemeris and Calibration Processing System

1. Interface to the MCS processing system to receive tracking data and send reference ephemerides and calibration information.

2. Generate reference ephemerides for all spacecraft.

3. Analyze vehicle tracking data to detect, correct or compensate for systematic deviations from model predictions.

2.2 Design Requirements

a. Raw tracking data will be collected from the monitor stations hourly.

b. The ephemeris and clock correction estimators will be executed every 12 hours.

c. The ephemeris and clock predictions will be generated daily and uploaded daily into all spacecraft.

d. The reference ephemeris will cover a 15-day span and will be generated every seven days.

e. Software development and maintenance will utilize interactive services of the MCS processor with minimal impact on the operational activities.

f. The MCS processing requirement is estimated at a minimum 123 thousand instructions per second for application programs and direct requests to the operating system to complete the load generation sequence during Phase I. If it is assumed that this load can be carried efficiently by a multiprogramming operation system, it is reasonable to expect two-thirds of the available CPU power put to productive use, with the remaining one-third going to system overhead and CPU idle time. This gives a 185 thousand instruction per second requirement with no safety factor or attempt to minimize software development costs.

   During Phase IIA, the upload sequence time line may include the generation of messages for 5 or 6 of the 12 satellites at a time. With the closely spaced satellites giving time constraints similar to those in Phase I, the minimum requirement may be 230 to 270 KIPS.

   These estimates do not include attempts to account for:

   1) re-tries of all or portions of the upload sequence due to error or unreasonable results. This capability is needed to recover and still upload the spacecraft without substantially cutting the scheduled test time. This capability requires:

- checkpoints throughout the sequence with pertinent information available for display to the analyst.

- Analyst's ingestion of performance indicators (some automatically presented, some queried for), decision, and entrance of GO/ABORT/RETRY (possibly with parameter change) command. Five minutes per sequence have been allowed in the above estimation, assuming no RETRY's.

- Resumption of the sequence with either the next processing step, or a re-try of one or more previous steps.

2) Execution requirements of a program are greatly influenced by criteria, applied to the programming effort.[1] Weinberg, in an article[2], compared two programming groups given the same program specification but the different criteria of minimizing development time or program execution time. The group concerned with execution times produced programs that ran average of six times faster than the other group, but took an average of twice as many runs to develop. The criteria of minimizing development costs and maintaining a tight schedule may have significant effect on program execution rates and machine loading.

3) An aspect of programming criteria similar to "b" is involved in the use of structured programming. This approach attempts to minimize development costs by imposing rigid programming standards to structure the control flow of the program, make the control flow obvious to someone scanning the code, and minimize the testing effort via a "top-down" approach to development and test. Again, the emphasis is on development cost, not execution efficiency.

4) Added software development costs are incurred when there is little or no excess capacity in the processor. As constraints of the processor are neared, programs must be redesigned, standards waived, and various gimmicks employed to utilize the amount of processor capability that is potentially available. Added costs accrue due to additional programming and schedule slippage.

5) Requirements for additional processing during the upload sequence that may emerge during development and demonstration of the ground control segment. These may include an additional analysis or verification step in the sequence, a more complex clock state estimator and predictor, or some other change in technique in order to better the navigation performance.

The processor procured should have excess capability to account for the above and minimize total program costs. Processor capability 50% to 100% in excess of the minimum required is recommended.[1] With an average of 75%, the requirement becomes 325 KIPS (during Phase I) with the capability to increase to between 400 KIPS and 475 KIPS (during Phase IIA). The Phase IIA increase should not be interpreted to mean that the addition of a second processor will satisfy the requirement, since historically this technique has had substantial impact on software costs and schedule slippages.

g. The MCS central memory requirement is estimated to be a minimum of 40K (K=1024) words (based upon 32 bits per word) for application oriented software. To this is added an estimated 16K word for the operating system giving a total requirement of 56K words.

For the reasons discussed in "f", excess capacity should be included in the processor requirements. As the program load nears the memory capacity, either software development costs rise as the programs are squeezed down to fit or the processor speed requirement is increased to account for different program techniques used and extra operating systems overhead. A rule of thumb similar to that used in "f" suggests a 50% excess capacity for applications memory or 60K. This gives a total size of 76K words including the operating system.

The operating system should have a primary memory management capability, reducing the effects of a constraint imposed by memory size. For this reason, the excess memory capacity is less important than excess CPU capacity; a 65K word (256K character) memory would probably induce no costly constraints.

h. The reference ephemeris production CPU load is estimated at 1.7 billion instructions per satellite for 15 days of ephemeris. This estimate applies to a machine with a high precision word length (60 bits) and will be higher if a shorter word length machine, which would require extended precision processing, is used. The central memory requirement is estimated to be about 40,000 sixty-bit words or 60,000 to 75,000 thirty-two bit words.

See Section 2.4.2 for the derivation.

2.3 Schedule

The schedule in Figure 7-1 shows the anticipated periods of activity and pertinent events during Phases I and IIA. Important dates, other than satellite launches, are:

April, 1975 - Start of test and demonstration of four satellite navigation.

January, 1978 - End of Phase I; DSARC commitment to limited operational capability and Phase II; start of Phase IIA.

December, 1981 - Control segment augmented (if necessary to support Phase IIB operational commitments).

2.4 Reference Ephemeris Generation

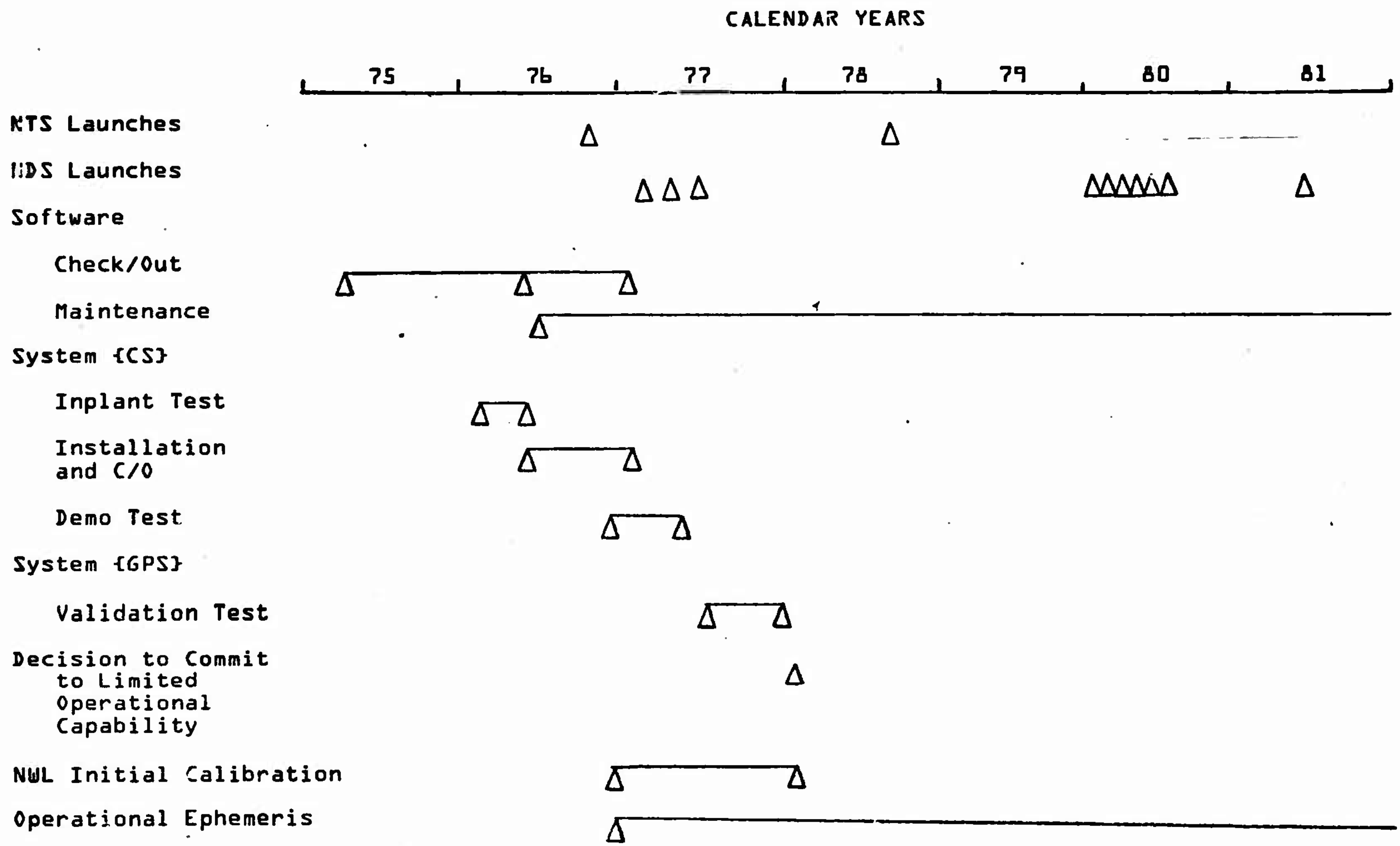
2.4.1 NWL Ephemeris Generation Service

NWL will generate a reference ephemeris using a version of the CELEST program. System calibration will result from analysis of CELEST output and modifications to the models and techniques in CELEST. A test and integration function will be required to incorporate modifications in the production version of CELEST.

The NWL charges for computer time to generate the reference ephemeris are estimated as follows:

ASSUMED:

- Computer charge of $100 per day of ephemeris for four satellites (estimate received from NWL).



GPS SCHEDULE

Figure 7-1

- 15 days of ephemeris generation done every 7 days.
- Cost is linearly proportional to number of satellites.
- 10% of the production work will have to be rerun to correct for errors.

THEREFORE:
- $1,500/week for four satellites + rerun.
- = $78,000/year for four satellites + rerun.
- + $19,500/year/satellite + rerun.
- $5,400 per quarter per satellite.

GPS will have to ship the tracking data to NWL and then ship the ephemeris outputs back to the MCS each week. This will be done by data transmission over some communication network, at a weekly cost of $80.

Table 7-1 gives a summary of parts of the ephemeris production costs for NWL:

- Included
  - computer time for ephemeris generation for all launched vehicles.
  - an additional 10% factor for reruns of the production program.
  - cost of data transmission between the MCS and NWL.
- Not included
  - cost of generation and maintenance of a production version of CELEST (man and machine costs).
  - cost of program and data storage at NWL.
  - cost of NWL support for analysis and calibration of CELEST models.

TABLE 7-1

PRODUCTION EPHEMERIS CHARGES

Quarter (Calendar	Year)	S/C NTS	S/C NDS	Current ($1,000) Quarterly	Current ($1,000) Yearly	Accumulative ($1,000) Yearly
4 Q	76	1	0	6.4	6.4	6.4
1	77	1	2	17.2		
2		1	3	22.6		
3		1	3	22.6		
4		1	3	22.6	85.1	91.5
1	78	1	3	22.6		
2		1	3	22.6		
3		2	3	28.0		
4		2	3	28.0	101.3	192.8
1	79	2	3	28.0		
2		2	3	28.0		
3		2	3	28.0		
4		2	3	28.0	112.1	304.9
1	80	2	6	44.2		
2		2	6	60.4		
3		2	9	60.4		
4		2	9	60.4	225.5	530.4
1	81	2	9	60.4		
2		2	9	60.4		
3		2	10	65.8		
4		2	10	65.8	252.5	782.9
1	82	2	10	65.8		
2		2	11	71.2		
3		2	11	71.2		
4		2	12	76.6	284.9	1067.8

Table 7-2 gives a summary of costs similar to Table 7-1, but includes an arbitrary doubling of the computer charges (from \$100 per day of ephemeris to \$200) to show sensitivity to ephemeris generation costs.

Figure 7-2 shows the accumulated ephemeris costs through 1981.

2.4.2 Ephemeris Generation Processing Requirements

The production ephemeris generator will be a version of the NWL program CELEST in order to use existing results of R&D efforts at a minimal cost to GPS.

CELEST currently runs on a CDC 6700 at the Naval Weapons Laboratory in Dahlgren, Virginia. It is a FORTRAN program that is segmented to run in 43,600 ($\approx 125,000_8$) sixty-bit words, and it can be executed using either or both of the 6600 and the 6400 CPU's (the CDC 6700 has two programably identical CPU's which differ in speed, but can be applied alternately to the same program).

2.4.2.1 CPU Load

The charging structure for NWL users is:

charge = rate * system seconds.

The rate is based on the job's priority; higher priority jobs run sooner, cost more, and have restrictions on the system resources that they can use. The priorities, with charges and resource restrictions, are:

Priority	Rate	Maximum Time	Maximum Memory	Maximum Tapes	Maximum Private Pacs
4	\$0.24	180s	$60K_8$	0	0
3	0.18	1 hour	$140K_8$	3	1
2	0.12	--	$220K_8$	6	2
1	0.06	--	--	--	--

CELEST is restricted to a priority 3 or lower due to its memory requirements. Priority 2 probably gives overnight turnaround; priority 1 probably gives weekend turnaround. Priority 3 is unlikely to be used due to cost and the fact that no job run on a weekend is currently charged above priority 2. It is assumed that

TABLE 7-2

PRODUCTION EPHEMERIS CHARGES
{DOUBLED}

Quarter {Calendar Year}		S/C NTS	S/C NDS	Current {$1,000} Quarterly	Current {$1,000} Yearly	Accumulative {$1,000} Quarterly
4 Q	76	1	0	11.8	11.8	11.8
1	77	1	2	33.4		
2		1	3	44.2		
3		1	3	44.2		
4		1	3	44.2	166.1	177.9
1	78	1	3	44.2		
2		1	3	44.2		
3		2	3	55		
4		2	3	55	198.5	376.4
1	79	2	3	55		
2		2	3	55		
3		2	3	55		
4		2	3	55	220.1	596.5
1	80	2	6	87.4		
2		2	9	119.8		
3		2	9	117.8		
4		2	9	119.8	446.9	1043.4
1	81	2	9	119.8		
2		2	9	119.8		
3		2	10	130.6		
4		2	10	130.6	500.9	1544.3
1	82	2	10	130.6		
2		2	11	141.4		
3		2	11	141.4		
4		2	12	162.2	565.7	2110.0

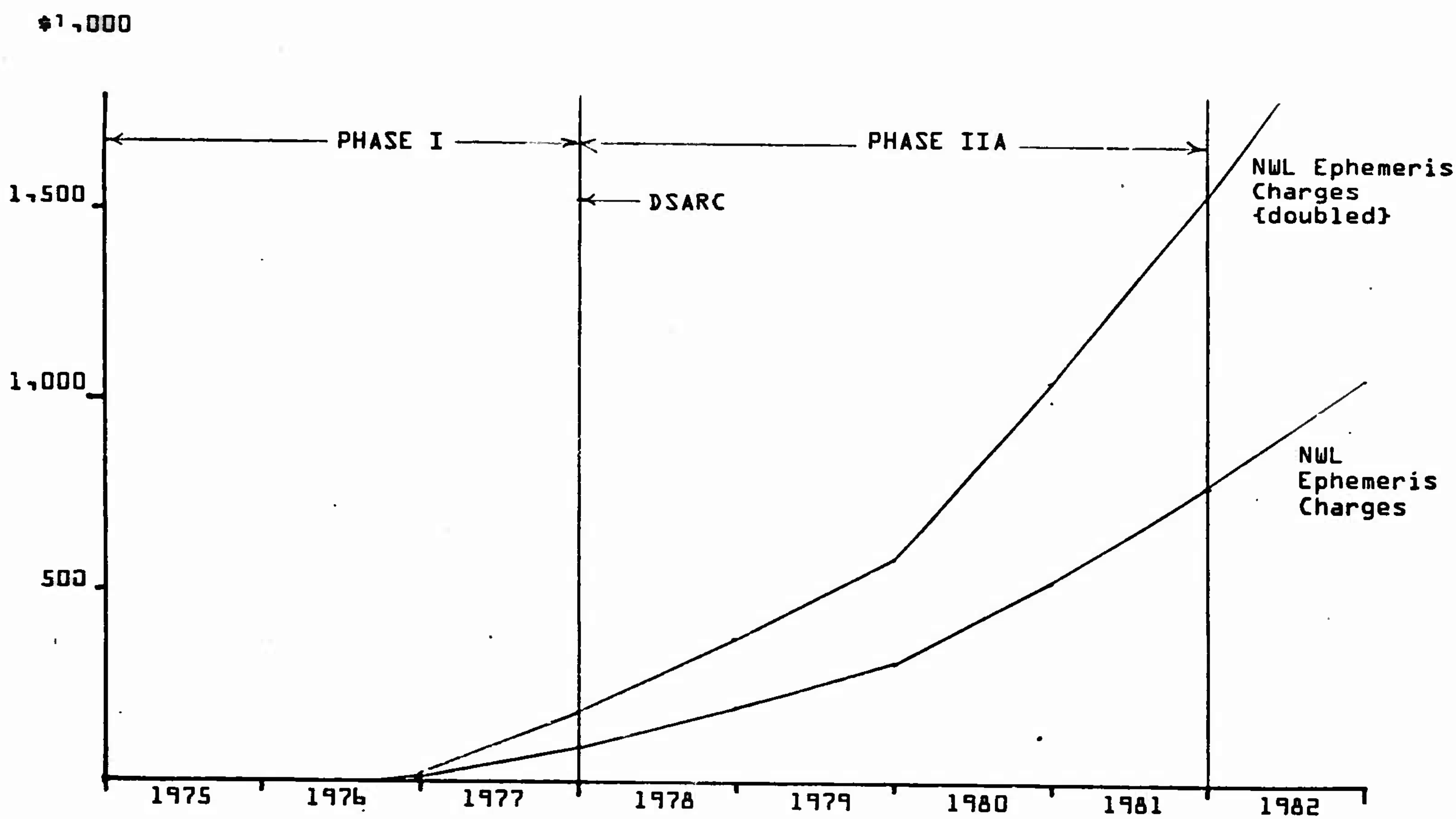


FIGURE 7-2
Ephemeris Cost

CELEST will be scheduled to run at priority 2 to keep cost minimal, but still ensure adequate turn-around. It is also assumed that cost estimates were based on this priority.

The estimated rate of $100 per day of ephemeris for four satellites is equal to a run charge of $1,500 per weekly run for the portions of Phase 1 with four spacecraft flying. This is equivalent to 12,500 system seconds of computer usage at priority 2.

NWL computes a system second by the following formula:

$$\text{system seconds} = (3*X+1*Y+.1*Z)*M/32K$$

- X = 6600 CPU seconds
- Y = 6400 CPU seconds
- Z = Peripheral processor seconds (measure of I/O)
- M = Memory used by the program.

If the PP time is assumed to be accumulated at a rate of 1/3 the 6400 time or 1/9 the 6600 time, the weekly run can be estimated to take the following 6600 CPU time from the above formula:

$$\begin{aligned}\text{system seconds} &= (3*X+1*Y+.1*Z)*M/32K \\ &= (3*X+1*0+.1*(X/9))*M/32K \\ &= \left(3+\frac{.1}{9}\right)*X*M/32K \\ &= \frac{27.1}{9}*X*M/32K\end{aligned}$$

$$X = \text{System seconds}*\frac{32K}{M}X\frac{9}{27.1}$$

$$\begin{aligned}6600\ \text{CPU} &= 12{,}500 * \frac{32{,}768}{43{,}600} * \frac{9}{27.1} \\ &= 3120\ \text{seconds} \\ &= 52\ \text{minutes.}\end{aligned}$$

Since CELEST runs the computations for each spacecraft independently, this estimate can be reduced to a single spacecraft by dividing by four, giving an estimate of thirteen minutes of CDC 6600 CPU time per week per spacecraft. This would give:

6600 CPU	13 minutes
PPU	1.5 minutes
System	52 minutes (charging number)

The CDC 6600 CPU's average execution rate is three to four times the rate of the CDC Cyber 70/Model 72 CPU. The Model 72 has been estimated to execute a mix of instructions (defined in another analysis as typical of

the MCS processing) at a rate of 637 KIPS. A ratio of 3.5 to 1 places the CDC 6600 CPU at 2,230 KIPS average execution rate. The application of this rate to the 13 minutes of CPU time per satellite yields 1.7 billion instructions per satellite for fifteen days of ephemeris.

This estimate is based on the precision of the CDC 6600 word size of sixty bits. A machine with a shorter word length would require extended precision involving either more instructions or a speed measurement that assumed arithmetic and data movements based upon multiple word quantitities. This estimate is also linearly proportional to the cost of ephemeris generation due to the fact that the estimate was derived from an estimated cost of $100 per ephemeris day. A cost rise to $200 per day without a rate change would mean that each satellite really requires about 3.5 billion instructions for 15 days of ephemeris generation.

2.4.2.2 Memory Requirements

CELEST currently requires in excess of $43,000_{10}$ sixty bit words to run as an overlayed FORTRAN program. This probably could be reduced to around 40,000 sixty bit words with simple alterations and making sequences of overlays into sequences of programs. A production version would therefore require an estimated 60,000 to 70,000 thirty-two bit words of directly addressable storage (excluding the operating system) to execute. Altering the program to execute in less storage is assumed to require substantial programming effort to create the smaller version and to maintain it.

2.5 Criteria

The approaches will be analyzed and compared according to the criteria listed here. Quantitative assessments are not available for much of the capability and flexibility analysis. The cost figures presented are rough estimates and can only be refined when computer vendors submit proposals.

2.5.1 Capability

This criterion pertains to capability of the approaches to provide support for MCS control, MCS development, MCS maintenance, and ephemeris generation.

2.5.2 Flexibility

This criterion pertains to the ability of the MCS processor to support changes in GPS requirements. Included are processor loading, memory loading, peripheral loading, operational changes, and development of new techniques.

3.0 DESCRIPTION OF APPROACHES

The approaches describe an MCS computer that is a large "mini", or one that is a small "large-scale" computer that is capable of supporting the ephemeris generation function:

- Approach A1 - purchasing a large "mini" for the MCS processor; generating reference ephemerides at NWL through Phase IIA.
- Approach A2 - same as A1, but with different costs assumptions for the ephemeris generation.
- Approach B1 - purchasing a small "large-scale" computer; generating reference ephemerides at NWL through Phase I; generating reference ephemerides at the MCS during Phase IIA.
- Approach B2 - same as B1, but with a computer lease during Phase I and a purchase/conversion during Phase IIA.

3.1 Allocation of Functions to System Elements

The system elements involved are:

- Master Control Station, including its processor.
- NWL - Naval Weapons Laboratory, including its CDC 6700 computing system.

The functions are:

- MCS Software Development - design, development testing, and integration of all software to be executed at the MCS.
- MCS Control - the result of analyst effort and execution of software in the Master Control Station CPCI.
- CELEST Development - on-going R&D work at NWL, the result of which may not be incorporated into the production version of CELEST.
- CELEST Calibration - analysis and modification

of techniques and models in CELEST to improve GPS performance and based upon GPS data.

- CELEST Maintenance - generation modification and testing of the production version of CELEST used for GPS reference ephemeris generation.

- Reference Ephemeris Generation - periodic execution of a production version of CELEST to produce the reference ephemerides.

The approaches are classed according to their functional equivalence:

Approach A - Approaches A1 and A2, in which NWL continues to provide reference ephemeris throughout Phase II.

Approach B - Approaches B1 and B2, in which the MCS assumes the production of ephemeris work after Phase I. NWL continues to provide some calibration and maintenance activity.

The allocation of functions to system elements is shown in Table 7-3 .

3.2 Approach A1

The MCS processor is sized for the MCS requirements through Phase IIA. NWL provides the reference ephemerides weekly through Phase IIA.

3.2.1 MCS Processor

A large version of a small to medium scale computer is procurred in April, 1975 to begin machine check-out of the development software. The system has a block configuration as shown in Figure 7-3 . The processor is the fastest model in a compatible line, its memory is close to the maximum that is directly addressable by any one program. Pertinent statistics for this processor are:

MCS mix speed	450 KIPS
Floating point precision	24 or 48 bits
Memory size	65K thirty-two bit words
Purchase cost	$600,000

TABLE 7-3

FUNCTION ALLOCATION

Function	Approach A	Approach B
MCS Development	MCS	MCS
MCS Control	MCS	MCS
CELEST Development	NWL	NWL
CELEST Calibration	NWL	NWL
CELEST Maintenance		
- Phase I	NWL	NWL
- Phase IIA	NWL	NWL + MCS
Reference Ephemeris Generation		
- Phase I	NWL	NWL
- Phase IIA	NWL	MCS

MCS - Master Control Station

NWL - Naval Weapons Laboratory

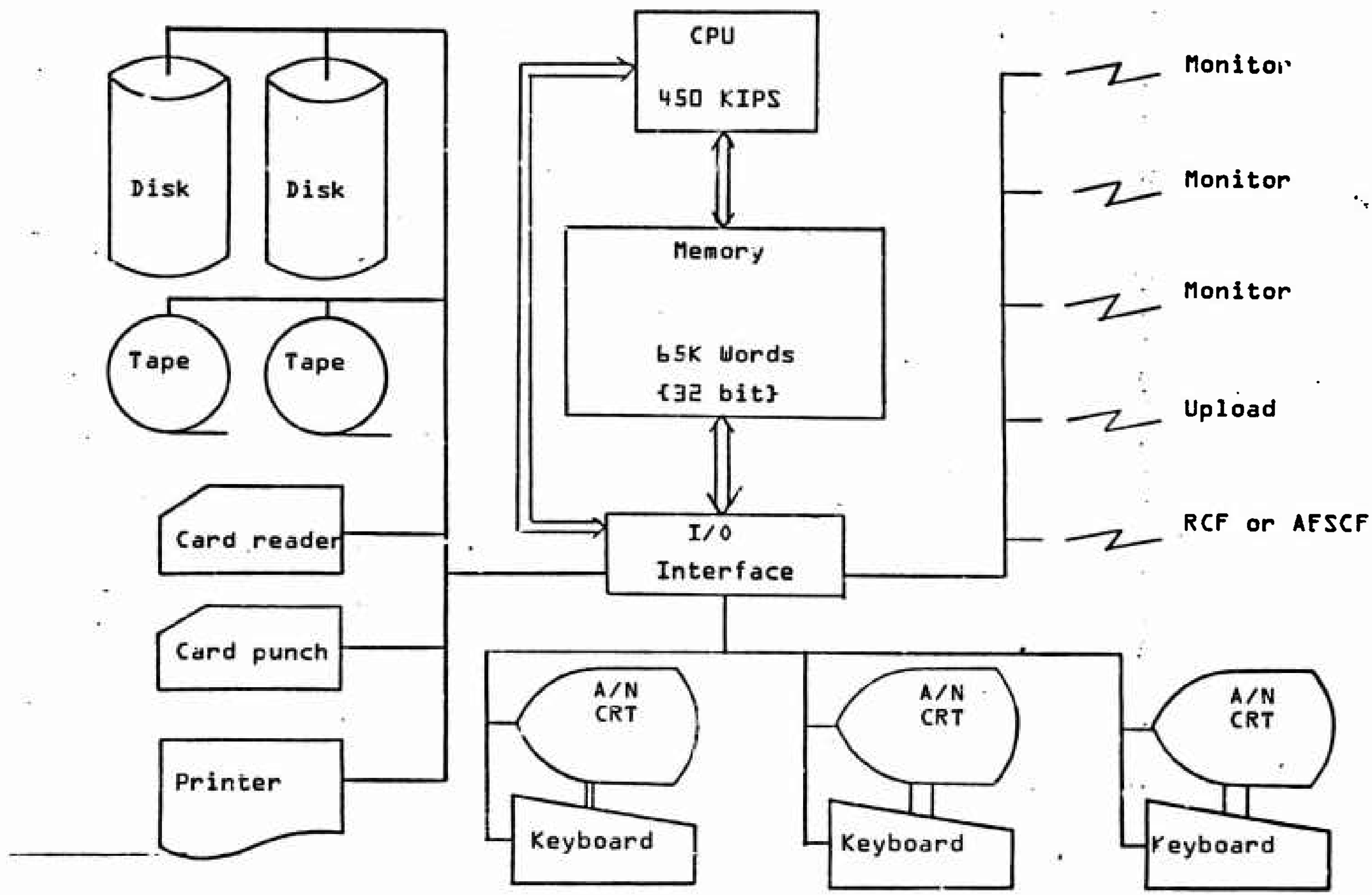


FIGURE 7-3
Configuration for Approaches A1 and A2

3.2.2 MCS Operating System

The vendor of the computer system supplies operating software to support development and operational activities. The operating system supports multiple tasks executing concurrently. These tasks are protected from a single batch job executing in the background, but are not protected from each other. The operating system allocates the CPU to the tasks on the basis of priorities and interrupts that have been detected. Provision is made for an application executive to initiate tasks and pass parameters to them. Software drivers are included for all peripherals.

Development tools include an interactive text editor, a FORTRAN compiler, and miscellaneous debugging aids. A file system manages mass storage allocations and allows the programs to use file addresses rather than disk locations. Utilities aid the dumping and restoring of disk storage.

3.2.3 Ephemeris Support

The reference ephemerides are generated weekly at NWL for the cost specified in Table 7-1

3.3 Approach A2

This approach is identical to Approach A1, except that the ephemeris generation charge is derived from Table 7-2 . This approach is included to show the cost effects of a variance in the service requirements for NWL's ephemeris generation service.

3.4 Approach B1

The MCS processor is sized for the MCS requirements through Phase IIA and reference ephemeris generation weekly during Phase IIA. NWL provides the reference ephemerides weekly through Phase I and periodic calibration and maintenance support thereafter.

3.4.1 MCS Processor

A small version of a large-scale computer system is procurred in April, 1975 to begin machine check-out of the development software. The system has a block configuration as shown in Figure 7-4 . The processor is the slowest model in a compatible line, the memory is close to the minimum that is available.

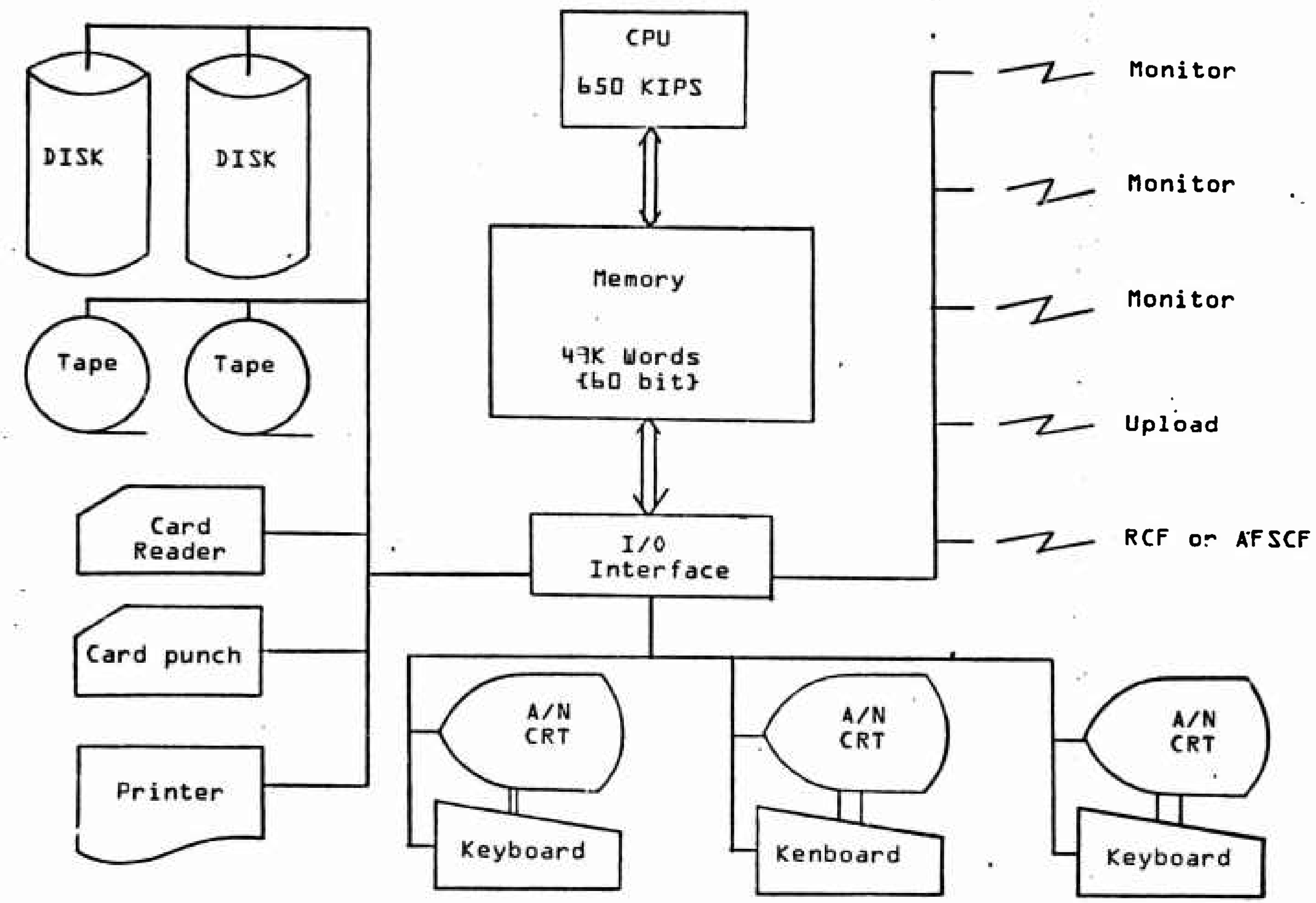


FIGURE 7-4
Configuration for Approaches B1 and B2

Pertinent statistics for this processor are:

MCS mix speed	650 KIPS
Floating point precision	48 bits
Memory size	49K sixty bit words
Purchase cost	$900,000

3.4.2 MCS Operating System

The vendor of the computer system supplies a general purpose time-sharing operating system to support development and operational activities. The system supports multiple interactive and batch jobs executing concurrently with automatic swapping of programs between mass storage and central memory based upon a dynamic priority scheme. All programs are protected from other programs. Provision is made for an application executive to initiate tasks and pass parameters to them. Software drivers are included for all peripherals; local I/O, remote batch, and interactive sub-systems are included to utilize the drivers for the various activities.

Development tools include an interactive text editor, a FORTRAN compiler, and miscellaneous debugging aids. A file system manages mass storage allocations and allows all programs to access data by file addresses rather than disk locations. Access restrictions may be placed on certain files to ensure data protection; multiple programs may access the same file concurrently with system provided interlocks. Utilities aid the dumping and restoring of data files.

3.4.3 Ephermeris Support

The reference ephemerides are generated weekly at NWL during Phase I for the cost specified in Table 7-1 . At the beginning of Phase IIA, the production version of CELEST is integrated into the MCS and Phase IIA reference ephemerides are generated at the MCS. NWL continues with periodic maintenance of CELEST and analytic support.

3.5 Approach B2

This approach is functionally equivalent to Approach B1. The computer system is leased for Phase I and purchased during Phase IIA. The lease rate is two percent of the purchase price per month and the lessee accumulates equity in the system equivalent to seventy percent of the total lease payments. The eventual purchase price is $900,000, less the accumulated equity.

4.0 COMPARISON

4.1 Capability

This section compares the capabilities of the alternates. The capabilities of Approaches A1 and A2 are equivalent and will be collectively discussed as Approach A. Approach B will refer to both Approaches B1 and B2.

4.1.1 MCS Operations

Both approaches have processing power in excess of the estimated MCS processing requirements. Approach A has a KIP capacity 40% in excess of Phase 1 sizing estimates; Approach B has 100% in excess. Approach A has a capacity equivalent to the expanded Phase 2A requirement; Approach B has approximately 40% excess capacity.

4.1.2 Ephemeris Generation

The estimate of 1.7 billion instructions per spacecraft per week produces the following CPU loads (note that the extended precision required in Approach A is not accounted for).

	per S/C	Phase I	Phase IIA
Approach A	1.05 hours	4.20 hours	12.6 hours
Approach B	.73 hours	2.91 hours	8.72 hours

At a running rate of 3 wall clock hours to 2 CPU hours (rough guess), the estimated wall clock times become:

	per S/C	Phase I	Phase IIA
Approach A	1.8 hours	7 hours	21 hours
Approach B	1.2 hours	5 hours	15 hours

This function is off-line with a time requirement of two to three days between input and output. In Phase I, the worst requirement is for 7 wall clock hours in two days for Approach A, along with the on-line processing:

- 15 minutes per hour for sample collection and pre-processing
- 45 minutes every 12 hours for correctors, predictors, and upload message generation.

If the 16.5 remaining hours a day are utilized for miscellaneous tasks at a rate of 50%, there are still up to 8 hours a day for this job, making it feasible.

In Phase IIA, the reference ephemerides could be staggered into 3 goups of four, causing the same attainable requirements.

Approach B is more feasible due to increased power.

Note that both processors must have operating systems that allow for the periodic suspension of the generation task to allow for higher priority activities and systems maintenance.

The memory requirements for CELEST make execution on the processor in Approach A infeasible since the execution of CELEST would require at least 76K for the operation system. Further compaction of CELEST would require substantial programming effort, both to create the smaller version and to incorporate the periodic maintenance modifications generated at NWL.

The memory in Approach B is adequate to hold both the program and the operating system. The operating system provides the dynamic memory management necessary to automatically suspend CELEST when higher priority activities, such as communication with the monitor stations, must occur.

The word size of Approach A would require reprogramming of CELEST to handle the precision required during portions of the computation. The impact of this activity on development of a production version and maintenance of that version reduces the feasibility of Approach A for this activity.

Approach B, due to its similarity with the NWL system, minimizes the effort required to create a production version of CELEST and maintain it at the MCS with NWL's tested modifications. The program could be kept in a form quite similar to NWL's version and changes made via utilities similar to NWL's.

Approach B can feasibly handle the generation of reference ephemerides, Approach A cannot without substantial additional effort.

4.1.3 Software Development

The MCS processor will be the primary tool for software development for the GPS control segment. During the initial development effort, operating systems software will affect the amount of software development required; interactive and batch development aids will affect the effort to develop the application software, as will the ability of the system to handle multiple concurrent users involved in different aspects of the development effort.

4.1.3.1 Operating System Functions

The MCS computer program requires certain operating system capabilities for its execution; additional software effort will be required to provide any of these capabilities that are not supplied with the vendor supplied operating system.

4.1.3.1.1 Job and Task Management

Both approaches allow the concurrent execution of several independent tasks, allocation of resources to those tasks, priority scheduling of execution or resumption of task execution based upon the occurrence of system events, external control and sequencing of task steps via a command language, and system response to a variety of program requests. Approach B offers a superset of Approach A's capabilities, including:

- concurrent execution of multiple interactive jobs, local batch jobs, and system utilities.

- an operating environment that is consistent for all user programs, allowing programs to be run interactively or in a batch mode with no recompilation.

- a command language which allows conditional sequencing of job steps using constants, arithmetic operators, relational operators, and Boolean expressions. These commands may be stored and accessed to allow execution of a complex job sequence by a single command.

- isolation of jobs simultaneously or concurrently utilizing the same system resources to provide protection to all other jobs in the system, should any program be in error.

- suspension of jobs and de-allocation of system resources to allow higher priority programs to execute before the lower priority job voluntarily relinquishes the CPU or central memory.

4.1.3.1.2 Resource Management

The operating systems in both approaches control and allocate system resources to requesting jobs based upon priority schemes. Approach B offers the following capabilities beyond Approach A:

- protection of resources that are not allocated to a job from any actions of that job.
- rapid re-allocation of central between concurrently executing jobs, some variable fraction of which are in central memory at any time. This is the ability to swap a program out of central memory at arbitrary points in its execution.
- executive control of unit record equipment to spool all input and output and allow terminal users to easily print various reports.
- logging of and accounting for all resource usage.

4.1.3.1.3 Data Management

Both approaches allow file creation, mass storage allocation, data storage and retrieval, and file deletion. Both also allow accessing of data in either a sequential or random fashion with some provision for translating a logical address within a file to a physical disk address. Approach B, designed for the time-sharing market place, offers these additional capabilities:

- data protection from unauthorized program access. Programs must request and be granted each type of access (read, modify, execute, create, or delete) that they wish for each file they wish to access. Thus programs not in the operational sequence can be denied access to the operational data base; and only those programs which are required to update the data operationally, can be allowed to alter the data in any manner.
- many programs can concurrently read data stored in the same file. A write interlock allows logical control of the updating process.

- extensive utilities allow the system to dump to tape and restore all permanent data files, to dump or restore selected files based upon various attributes of the files, to selectively archive files (maintain them in the file catalog, but retain their contents on tape instead of mass storage), and to report statistics on file usage.

- operational data and test data may be maintained in the file system with identical structures and identical file names, but under different user or account numbers. Thus, with one account number for operational programs and data, and another for development, development executions may be completely tested without requiring (or being granted) access to the operational data.

4.1.3.1.4 Recovery Management

Both approaches have the capability to detect and sometimes recover from various hardware, system, or application program malfunctions. Approach B offers extensive capability to maintain both files and currently executing programs across system malfunctions and re-starts.

4.1.3.2 Development Aids

The MCS processor will support the development of all MCS software; the development aids provided with operating system will influence the timeliness and cost of the development effort.

4.1.3.2.1 Interactive Text Editing

Both approaches offer an interactive utility for creating, modifying, listing, and saving program and data text. The extensive file management capability of Approach B facilitates the programmers' saving and retrieving text files more than the file system of Approach A.

4.1.3.2.2 Interactive Language Processors

Both approaches can compile FORTRAN programs from the terminal. Neither language processor converses with the terminal during compilation; each receives source code from a file (created during the editing process) and outputs a program listing and an error listing for optional display on the terminal. Both

can generate object code for interactive execution or batch execution. The same object code in Approach B can execute interactively or in batch mode due to the similarity of the batch and interactive subsystems.

4.1.3.2.3 Object Code Linkage and Manipulation

Both approaches allow linkage of object code modules into executable load units which may be overlayed.

Approach B offers extensive control of this process, generation of load and cross-reference maps, use of libraries of modules, name changing of selected sub-routines, and presetting memory to one of a variety of conditions to assist in debugging. Also in Approach B, selected routines may be recompiled, and the resulting code be merged into the old compiled code, negating the requirement to recompile the entire program.

4.1.3.2.4 Debugging Aids

Both approaches provide dumps of program memory, either after program termination or as snapshots at points during the program execution. The programmer may select breakpoints in the program flow, query for data values, change data values, and restart execution. Approach B provides additional capability for tracing of control flow, monitoring variables, and checking that array boundaries are not violated.

4.1.3.2.5 Documentation Aids

Approach B provides utilities and standards for incorporating external and internal documentation into the source code and culling this documentation to produce manuals.

4.1.3.3 Concurrence of Development Efforts

Approach B provides better response to the programmers than Approach A, due both to the greater capacity of the processor and to an operating system designed to service large numbers of varied users. Many unvalidated programs may be tested concurrently in the large-scale system, while the "midi" is limited to one unvalidated program at a time to ensure adequate system protection.

The structure of the system in Approach B allows development activity to run at a lower priority than operational functions but concurrently. Developed programs may be tested with duplicate data bases, allowing for extensive tests before access to the operational data base is permitted.

4.1.4 Continuing Maintenance

Maintenance of both hardware and software is expected during all phases of the GPS program. This section evaluates the tools provided by the MCS processor to assist in this function.

4.1.4.1 Hardware Maintenance

Both approaches provide diagnostic programs to help detect and isolate hardware malfunctions.

Approach A has exercisors which can be run during operational periods or maintenance periods. Outputs are saved and examined to determine the system health. Approach B has similar exercisors, but the quantity and quality are superior. On-line diagnostics, as well as operating system functions, note recoverable errors in a hardware error file while the system continues to function. The maintenance engineer, when alerted of possible trouble, has reports of all errors grouped by time of day, devices where errors occurred, channels involved in I/O errors, and other resources. Since one of these reports usually shows a clustering, the defective component is quickly determined. Off-line diagnostics are designed for use from a key-board and CRT display unit to allow quick isolation of probable defects before an oscilliscope is required.

4.1.4.2 Software Maintenance

The software maintenance activity involves system use similar to software development. The more extensive aids and the greater capacity of Approach B for concurrent diverse activities makes it better. In addition, software for remote terminal use (both interactive and batch) allows substantial maintenance effort to be performed at the contractor's location, requiring fewer and shorter trips to the MCS.

The addional complexity of B's operating system will require more maintenance activity than will A. However, the vendor of Approach B's software provides extensive and systematic maintenance service, correcting many bugs before they are encountered by a customer. The vendor of Approach A's software provides a similar, but less extensive service.

4.2 Flexibility

This section discusses the MCS processor's capability to adapt to changes in loading requirements. Such changes might result from deviations of actual loading requirement from estimations, operational changes, or additional development efforts to incorporate improved techniques during development and the GPS demonstration. The risk to the program is measured by the time and money required to adapt the MCS processor and software to the revised requirements. Because all approaches can easily handle decreased demands, only responses to increased demands are discussed.

4.2.1 Loading Variations

4.2.1.1 CPU Loading

Both Approach A and Approach B have excess capacity as a safety margin to handle deviations from loading estimates. Both approaches require no hardware changes as their capacity is approached, just additional software effort to utilize the processor more efficiently. Approach B, since it has more capacity than A, can adapt easier.

Should the loading exceed the processor capability, Approach A would require substantial time and money to adapt. A second processor would have to be procured because the processor used in Approach A is the fastest in its line. These two processors would have to be coordinated to share the work, an effort requiring re-design and re-development.

The processor in Approach B is the slowest in a compatible range of processors, allowing an upgrade in capability with no software change.

4.2.1.2 Memory Loading

Approach B has more memory than A allowing a greater deviation before any change is required. Approach B can more than double its memory capacity. Approach A can double its memory.

4.2.1.3 Peripheral Loading

Substantial growth capability exists in both alternatives. Approach A is less able to accommodate the increase CPU and memory loads necessary to handle the additional peripheral capability.

4.2.2 Operational Changes

A change in operations, such as the addition of verification steps in the upload sequence, could have substantial impact on the amount of processing required in a specified time. The approaches would adapt as indicated in 4.2.1.

4.2.3 Additional Development

Additional development efforts are affected by the development tools available to the programmers, the special techniques required to ensure that the processor capability is not overextended, the ability of the processor to support operational and development activities concurrently, and the additional processor capacity required to support the developed capability. Approach B has additional capacity and can support concurrent operations easier, and with more protection to the operational sequences than Approach A.

4.3 Cost

Costs are estimated through the calendar year 1981. This covers Phase I and Phase IIA testing periods. The two important points of cost measurement are the total Phase I cost (as of DSARC at the start of 1978) and the total cost through 1981.

4.3.1 Phase I Costs

4.3.1.1 Non-Recurring Costs

4.3.1.1.1 Hardware Acquisition

Approaches A1 and A2 both cost $600,000. Approach B1 costs $900,000. Approach B2 has no Phase I acquisition cost.

4.3.1.1.2 Software Acquisition

Approaches A1 and A2 both have an estimated cost of $20,000. Approaches B1 and B2 use a software license with a $5,000 initial fee.

4.3.1.1.3 Site Preparation and Installation

The PRELORT building has adequate air-conditioning power and raised flooring for all alternates. This is assumed to be government furnished. The processors in Approaches B1 and B2 require water-cooling

and extra space for motor generation equipment. It is assumed that the cooling tower outside the building will be GFE and that a concrete pad and shed need to be constructed for the motor generator sets of B1 and B2. If space (100-200 square feet) can be found in the existing machine room, the estimated $10,000 cost for Approaches B1 and B2 would be reduced substantially.

The installation and freight charges for Approaches A1 and A2 are estimated at $7,000 (rough). Installation and freight for Approaches B1 and B2 are provided by the vendor.

4.3.1.2 Phase I Recurring Costs

4.3.1.2.1 Hardware Lease

Approaches A1, A2 and B1 involve no hardware lease. Approach B2 has a lease cost of $18,000 per month.

4.3.1.2.2 Software License

Approaches A1 and A2 have no software license fees. Approaches B1 and B2 have a license fee of $2,000 per month.

4.3.1.2.3 Hardware Maintenance

In all approaches, it is assumed that the processor vendor will provide preventative and emergency maintenance services. In Approaches A1 and A2, this is estimated at $2,000 per month; in Approaches B1 and B2, the cost is estimated at $3,000 monthly.

4.3.1.2.4 Software Maintenance

In all approaches, the vendor will supply some maintenance services for vendor standard software at no additional charge.

4.3.1.2.5 Operating Costs

All approaches require similar resources and manning to operate. Approaches B1 and B2 require more power and cooling, but this is assumed to be GFE.

4.3.1.2.6 Ephemeris Generation Service

The cost of creating and maintaining a production version of CELEST is assumed identical for all approaches and is not included. The cost of ephemeris generation during Phase I is $91,500 for

Approaches A1, B1 and B2; and $177,900 for Approach A2.

4.3.2 Phase IIA Costs

4.3.2.1 Phase IIA Non-Recurring Costs

4.3.2.1.1 Hardware Acquisition

Approach B2 has a hardware purchase conversation at this point for a one-time charge of $446,000. The other approaches involve no hardware acquisition.

4.3.2.1.2 Software Acquisition

No costs for any of the approaches assuming no new vendor software is desired.

4.3.2.1.3 Site Preparation and Installation

No costs incurred for any approach.

4.3.2.2 Phase IIA Recurring Costs

4.3.2.2.1 Hardware Lease

Approaches A1, A2 and B1 involve no hardware lease. Approach B2 has a lease cost of $18,000 per month for the three months before the system is purchased.

4.3.2.2.2 Software License

Approaches B1 and B2 have a license fee of $2,000 per month for the first three months.

4.3.2.2.3 Hardware Maintenance

There is no change from Phase I. Approaches A1 and A2 cost $2,000 per month; Approaches B1 and B2 cost $3,000 per month.

4.3.2.2.4 Software Maintenance

Same as Phase I: no cost.

4.3.2.2.5 Operating Costs

Same as Phase I: no costs included.

4.3.2.2.6 Ephemeris Generation Service

In Approaches A1 and A2, NWL continues to supply this

service for a cost of $691,000 and $1,366,000 respectively. In Approaches B1 and B2, production ephemeris generation is transferred to the MCS; a one-month overlap charge of $7,400 is included.

Alterations to the production version of CELEST will originate from NWL at a cost which is not included here, but is identical for all approaches. Approaches B1 and B2 involve integration of the production version of CELEST into the MCS processing system. An additional cost of $20,000 is estimated for Phase IIA.

4.3.3 Cost Summary

The costs are summarized in Table 7-4 . Figure 7-5 shows the accumulated costs as a function of time. Neither summary includes the impact of the approaches on software development costs.

TABLE 7-4

COST SUMMARY

Item	Approach Cost (x$1000) A1	A2	B1	B2
PHASE I				
Hardware Acquisition	600	600	900	0
Software Acquisition	20	20	5	5
Installation	7	7	10	10
Hardware Lease	0	0	0	594
Software License	0	0	66	66
Hardware Maintenance	66*	66	99	99
Software Maintenance	--	--	--	--
Operating Costs	--	--	--	--
Ephemeris Generation	92	178	92	92
TOTAL	785	871	1172	866
PHASE IIA				
Hardware Acquisition	0	0	0	446
Software Acquisition	0	0	0	0
Installation	0	0	0	0
Hardware Base	0	0	0	54
Software License	0	0	6	6
Hardware Maintenance	96	96	144	144
Software Maintenance	--	--	--	--
Operating Costs	--	--	--	--
Ephemeris Generation	691	1366	27	27
TOTAL	787	1462	177	677
PROGRAM TOTAL	1572	2333	1349	1543

*equivalent for all alternatives

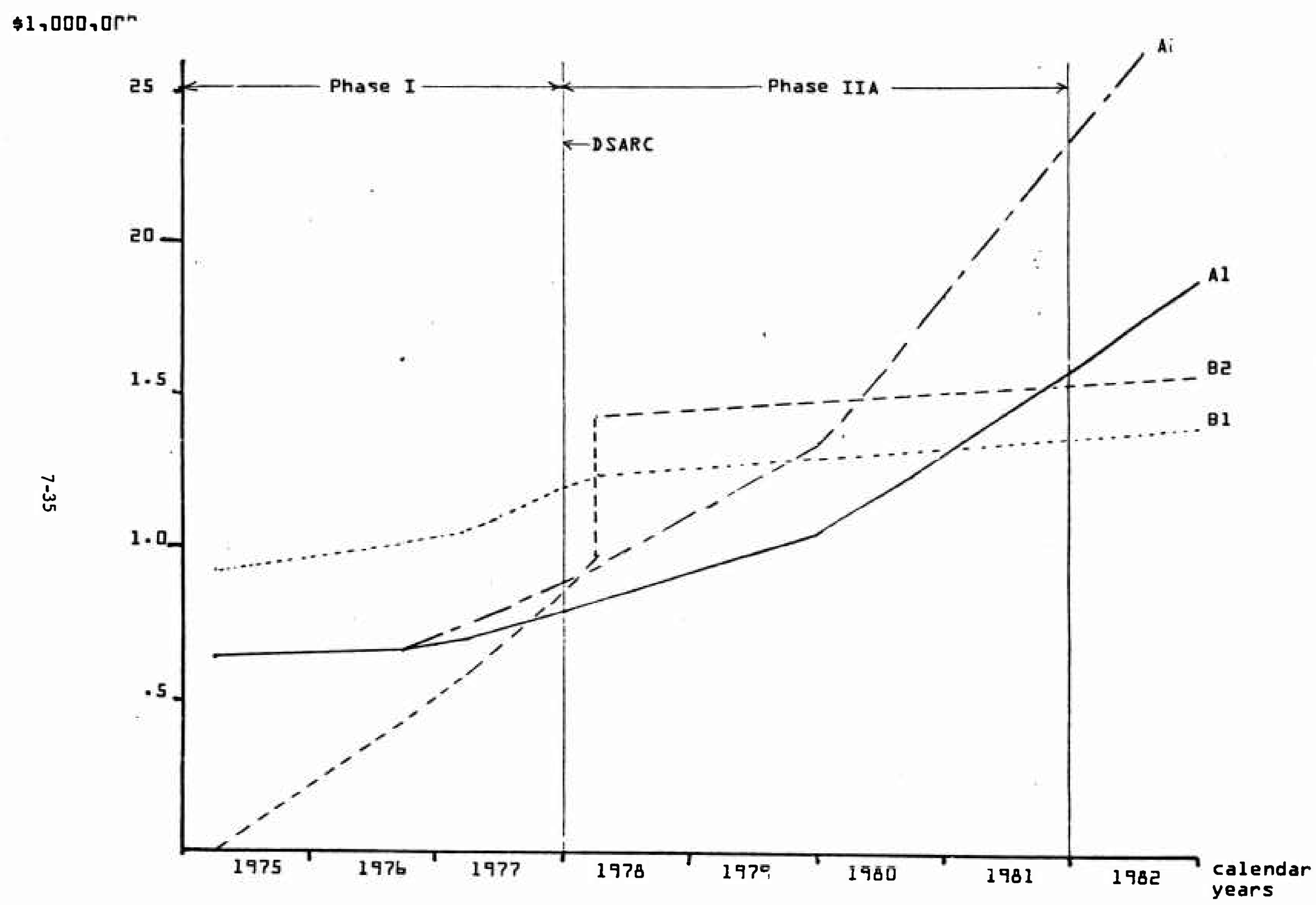


FIGURE 7-5
Cost Summary

5.0 CONCLUSION

The driving Phase I costs are equipment procurement and software development. The driving Phase IIA costs are system operation and ephemeris generation.

In Phase I, Approaches B1 and B2 offer more capability as development tools and less risk, but the quantitization of these benefits has not been attempted. The major costs show B1 as substantially more in Phase I than A1, A2, and B2. In Phase IIA, Approaches B1 and B2 show significant cost savings in the ephemeris production. In Approach B2, these cost savings are applied to a delayed purchase of the processor.

Approach B1 shows the lowest overall cost, the least risk, and the highest performance of the approaches. Its high initial cost makes it the recommended approach only if the program has a high probability of continuing through Phase II, and has the money to spend initially to effect overall savings.

A low initial budget and a reasonable probability that the program would continue through Phase II would suggest Approach B2. This approach has a higher overall cost than Approach B1, but the commitment to spend the money is not required until after the decision to carry the program through Phase II.

Approaches A1 and A2 (note that the two approaches do not imply a capability to choose between them, but that the cost will vary for Approach A probably between these two approaches) offer the best solution should the program have a low probability of continuing through Phase II. The Phase II costs guarantee that Approach A would have the highest overall cost, except for the low probability of spending Phase II money. Approach B2 shows similar Phase I costs to Approach A1 and A2, but a decision to defer Phase II requires that the program lose the equity accrued in the equipment or spend additional money to purchase it (a ready market in the government for the equipment at the conversion cost is probable, but not guaranteed). The advantages of Approach B2 are proportional to the probability of continuing through Phase II.

FOOTNOTES

1. Boehm, B. W., "Software and Its Impact: A Quantitative Assessment", DATAMATION, May 1973.

2. Weinberg, G. M., "The Psychology of Improved Performance", DATAMATION, November 1972.

REPORT C 8

EPHEMERIS DETERMINATION ANALYSIS

REPORT C 8

EPHEMERIS DETERMINATION ANALYSIS

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1.0 INTRODUCTION

2.0 REQUIREMENTS

Fundamental to the successful development of the GPS is the achievement, through on-line determination of satellite ephemerides and satellite clock-model parameters, of a user equivalent range error (UERE) on the order of 12 feet. In the design of the ephemeris and clock-modelling algorithms, it is important to recognize that overall system performance, measured in terms of UERE or user geopositioning, is the primary performance criterion, and that the interactive processes between ephemeris and clock determination may introduce correlated errors exceeding, but notimpacting, the required UERE.

Functionally, the ephemeris and clock-model determination software is required to translate pseudoranging data into estimates of satellite and clock states, meeting the quantitative design requirement on UERE, and additionally, to determine any related model parameters, such as radiation pressure which can inhibit the maintenance of this UERE over extended periods of time and space. Due to the highly interactive nature of satellite and clock states and the immunity of the system product (UERE or geopositioning accuracy) to correlated errors in these states, their estimation must be considered in the overall system sense.

3.0 CRITERIA FOR SELECTION

In addition to the achievement of a budgeted User Equivalent Range Error, as discussed above, three other qualitative design goals have been considered. These are:

- Legacy -- The algorithms and related software products must permit orderly growth of the GPS, from demonstration phase to full operational deployment, without major revisions in the data processing concept and supporting software. (It is anticipated that the CPU loading will grow as the system matures, and that this growth can be accommodated by additional small processes or by growth within a CPU family.)

- Cost and Technical Risk - - Experience has shown that large CPCI's tend to increase the risk from cost and technical standpoints, due principally to lack of communications between many programmers developing a CPCI. Better control over cost, schedule and technical performance can be maintained by distributing the processing, where technically feasible, over smaller CPCI's with careful interface definition and control.

- Utilization of Government Resources --Within the government community disciplined resources (personnel and software) exist, and their utilization on a limited basis -- particularly during the demonstration phase for calibration of the overall system and its components (sensor locations, geopotential model, etc.) -- would significantly reduce the cost and technical risk. In subsequent discussions, the utilization of Naval Weapons Laboratory resources, already integrated into the DMA community, will be proposed in an off-line, supporting role.

Each candidate system has been evaluated against these design goals.

4.0 ALTERNATIVE APPROACHES

Methods investigated to support the ephemeris and clock state estimation have been generally restricted to linear differential-correction procedures representing common astrodynamic practice in the precise determination of satellite orbits. Since predicted ephemerides are required to support the navigation process, the satellite state estimates must be made under dynamical (or force model) constraints which will support this prediction process over extended periods; the differential-correction procedures provide this mechanism.

Variations on the implementation of differential correction techniques considered for GPS include both simultaneous multivehicle processing, wherein all satellite and clock states are estimated simultaneously, and a distributed processing concept wherein satellite and clock states are separately estimated, but in such a way as to protect correlated errors which serve to reduce the UERE. Within each method, variations on the filtering method have also been investigated. Analysis has demonstrated that either method will support the required UERE, although in their implementation, there is a significant difference in computational implementation and related factors of cost, risk and legacy.

4.1 Simultaneous Multivehicle Processing

In the simultaneous concept, all pseudo-range observations are pooled to simultaneously estimate ephemeris and clock states. Typical of this implementation technique is the TRACE program, developed by Aerospace Corporation. This implementation technique will generally result in higher accuracy, since at all times enough degrees of freedom (solution parameters) are available to properly account for their associated observation residual patterns. From the standpoints of legacy, cost and risk, the simultaneous concept, however, tends to be unwiedly. To manipulate the covariance matrix alone, for example, requires:

Phase	Number of Satellites	Stations	Solution Parameters*	Computer Words
I	4	3	42	903
II	9	4	87	6786
III	24	5	224	25200

(should a batch or batch-sequential least-squares filter be used, a similar number of words would be required for the inverse). While this single example is not conclusive in itself, experience has shown that multiprocessing concepts equate to large computational and machine requirements, and due to their sheer size, also tend to be long on cost and schedule risk.

* Based upon six state parameters and one model parameter per satellite and two clock-state parameters (offset and rate) per clock (except master.)

4.2 Distributed Processing

The distributed processing concept tends to decentralize the processing load into smaller portions, to be serviced by small machines which can be time-shared with other processing tasks. In this way, the computational elements of the system can be more efficiently utilized, and system growth is more readily accomplished.

In any distributed processing concept, it is necessary to isolate the ephemeris determination and clock modeling processes, yet preserve their interaction (in terms of correlated errors) in the final products. The key to this concept is to utilize pseudorange <u>differences</u> between consecutive pseudorange values (a data type identical to "integrated doppler") for ephemeris determination. Since clock offsets are manifested as biases in pseudorange, the range differences are immune to offset errors.[1] In this way, the ephemerides can be updated, one-by-one, and a consistent model for all clocks then derived utilizing the derived ephemerides and pseudorange data. This processing concept is shown in Figure 8-1.

Subsequent discussions of simulation results will confirm that the UERE contribution of this concept will meet satisfactory performance levels for GPS. At this point, the advantages of this concept over the simultaneous multivehicle concept are:

- A single orbit determination and prediction module can service all satellites sequentially, and this module size is independent of the number of satellites.

- The clock-state determination module size will grow with the satellite population, but with full operational deployment, can still be implemented on a small computer.

[1] Note that in time-tagging the resultant range-difference data, errors of microseconds are inconsequential.

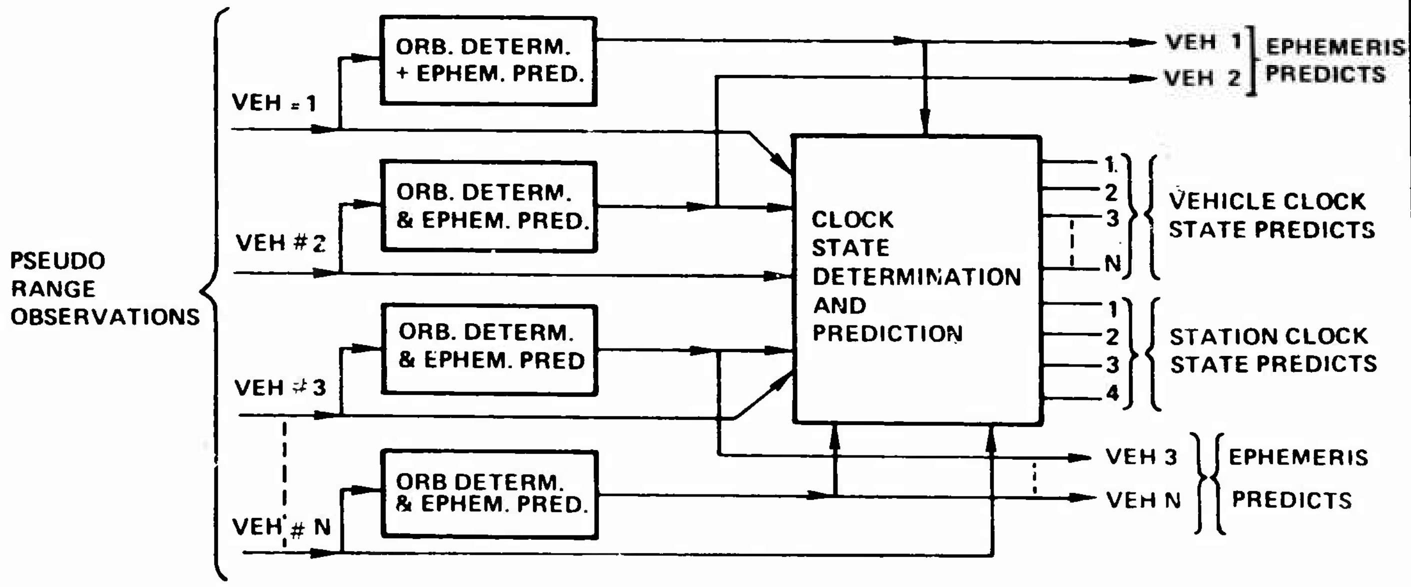

Figure 8-1 Distributed Processing Concept 4.2 (Cont.)

- Since the orbit and clock state parameters are subjected to different model constraints, the option to utilize different filtering concepts is available. Every effort will be made, however, to utilize common techniques and routines to simplify maintenance.

An additional consideration which will significantly simplify the deployment of the system, particularly during the demonstration phase, is that the bulk of the computational load is involved with the numerical integration of ephemerides and the computation (by analytic or variational equation techniques) of the orbit state transition matrices. (The clock state transition matrices are trivial.) This function can be accomplished off-line and, utilizing existing software and large-scale computer(s), even off-site, reserving to on-line processing only those functions of ephemeris and clock state updates, both highly linear processes if the externally provided ephemerides are sufficiently accurate to support the linearity assumption.[1] The baseline recommendation, outlined in Section 7.0 and supported by simulation studies documented in Section 5.0 and Appendix A, will take advantage of this fact.

5.0 ANALYSIS OF ALTERNATIVES

The analysis of the ephemeris and clock modelling processes has involved two generally parallel, but highly interactive steps, as shown in Figure 8-2. The first of these is simulation, wherein the basic input and environmental model data are processed for candidate satellite, tracking and user configurations. The simulation products are quantitative assessments of the products of the candidate system, expressed in statistical terms. The analysis tool utilized in these simulation studies is the TRACE-66 program, the most comprehensive simulation tool of its type.

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[1] Experimentation to date has demonstrated that errors approaching 1 km will not defeat this hypothesis. (See Appendix A)

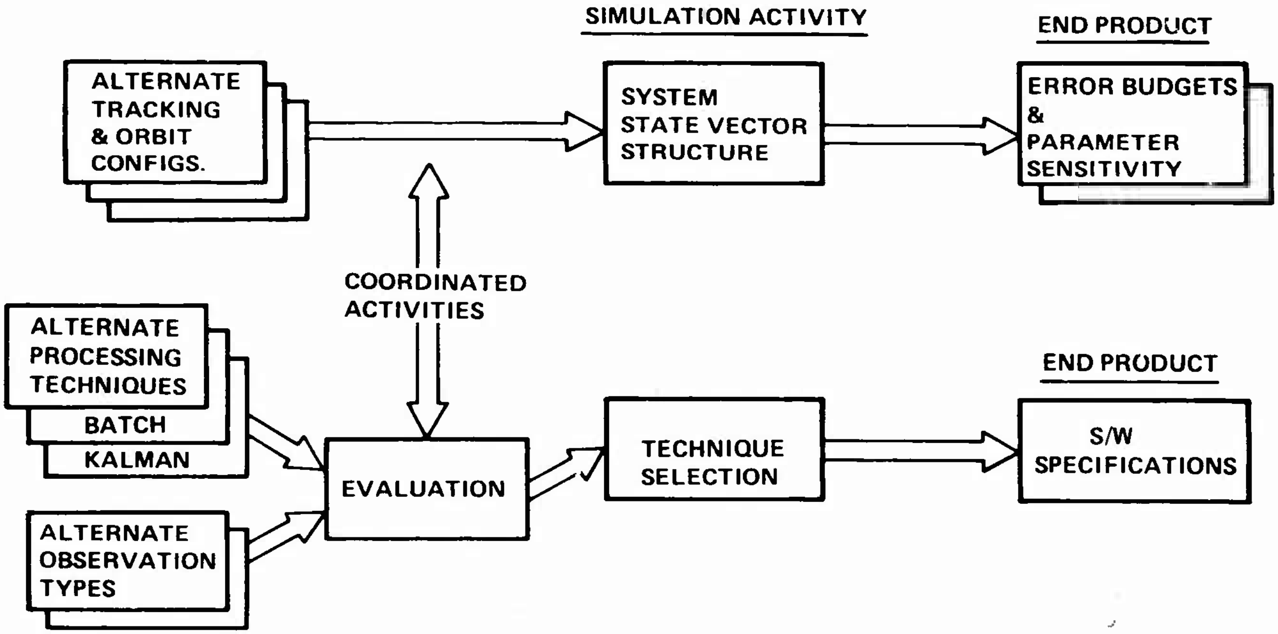

Figure 8-2 Ephemeris and Clock-Model Determination

The second step involves the development of algorithms to implement these processes, and some modest programming and experimentation with candidate algorithms to assess their suitability for on-line GPS applications. These algorithms have been restricted to the differential orbit correction procedures, although several variations on the basic differential-correction format and data filtering techniques have been considered. The products of this effort are quantitative assessments of computer speed and sizing, and qualitative assessments of complexity, growth capability and related operational considerations.

By interating between these simulation and implementation tasks, a baseline concept has evolved for the ephemeris and clock-modelling process.

5.1 Simulation Approach and Results

TRACE-66 provides a comprehensive tool to analyze the propagation of data and model errors through the entire GPS process. In the simulation studies, representative tracking data strategies were processed to determine the geo-positioning performance of a candidate satellite and tracking configuration, in the presence of environmental model errors, the latter introduced through the so called "Q" or "consider" parameter capability of TRACE. The product of the simulation analysis was the variance in the user's geopositioning, and by utilizing two values of user ranging error, it was possible to solve for the intermediate values of UERE and GDOP.

The following are the candidate tracking strategies and orbit support concepts which were considered in this simulation effort:

- Orbit configuration: SIGMA (See Part II, Report C-2)

- Tracking data: Pseudoranging data at 15 minutes intervals collected over a 48 hour period from the following locations representative of either AFSCF or NAG sites:

  Southern California
  North-Eastern United States
  Southern Alaska
  Hawaii

For the simultaneous multisatellite processing concept, pseudorange data from each station are processed. For simulations involving the distributed processing concept, greater accuracy was achieved by designating one station clock (southern Alaska) as a master clock and incorporating into the state estimation for each satellite the two satellite clock parameters (offset and rate); in this way, pseudorange data could be processed, with other stations contributing pseudorange differene data to the solution. Through this data management concept, the process reamins a distributed one(no interaction between the several orbit solutions) yet ephemeris products competitive with the multisatellite processing concept are obtained.

A ranging "sigma" of five feet was utilized as representative of the uncorrelated errors in smoothed observations taken at 15-minute intervals; the actual data rate would be higher to permit editing and smoothing. A range difference "sigma" of 0.005 ft/sec representative of uncorrelated errors in the difference of two pseudoranges taken 1000 sec apart.

- A priori orbit state statistics: A "steady-state" situation was considered, in which sufficient data had been processed to provide a priori orbit state data to the order of 800 feet in radial and cross-track coordinates and to 1300 feet and 2 feet/hour in in-track position and mean-motion, respectively. These data were readily introduced through initial statistics on the "F" and "G" orbit solution parameters. In addition, a 15 percent initial error in radiation pressure modeling was assumed. Since the navigation processing reduces these a priori errors by generally an order of magnitude, they have little effect on overall simulation results.

- Orbit state solution (P) parameters: Six orbit state parameters and one model parameter (radiation pressure) were estimated for each satellite. These states were estimated by a "batch least squares" filtering algorithm. While the adopted filtering algorithm will be selected on the basis of computational efficiency and ability to incorporate process noise, as well as accuracy, the batch least squares algorithm is representative of the several alternatives, in terms of accuracy, for this well conditioned problem.

- Clock state solution parameters: Two solution parameters, offset and rate, were estimated for each satellite clock, relative to an adopted system standard clock. For the multisatellite processing concept, TRACE resources permitted the simulation of the interrelationship of all ground clocks as well. The simulation results, in terms of UERE, are dependent only on the satellite clock interrelationships; however, in practice, all system clock parameters will be estimated regardless of the processing method. No relativistic effects are considered in the simulations, since they are manifested either as rate changes, already estimated, or as 12 and 24 hours periodic terms which are deterministic.

- User Solutions: User solutions were computed at 3, 9, 15, 21 and 27 hours after the observation span to assess system error variations with time and user location. The user locations which corresponded to these times were respectively: White Sands Missile Range, South Atlantic, Pakistan, and the Tasman Sea. For each one of these locations, two collocated users were solved for with different values of range "noise". A small value (σ_R=.1 Feet) was utilized to demonstrate the effects of orbit and clock state estimation uncertainties on the navigation products. A larger value (σ_R=1 Foot) was used to compute geometric dilution of percision (GDOP) for each user. By utilizing these two values of user navigation errors, user equivalent range errors (UERE's) were then computed with

$$\mathrm{UERE} = \sqrt{\sigma_{LAT}^2 + \sigma_{LONG}^2 + \sigma_{ALT}^2 + \sigma_{R\ BIAS}^2} \Big/ \mathrm{GDOP}$$

where σ_{LAT}^2, σ_{LONG}^2, σ_{ALT}^2, and $\sigma_{R\ BIAS}^2$ are respectively the variances in the user latitude, longitude, altitude, and range bias navigation uncertainties observed when σ_R = 0.1 feet.

- Consider Parameters: Consider or Q-parameters are those parameters not estimated (solved for) in the candidate orbit support concept, but which contaminate the GPS product. They are primarily environmental model errors and the primary source considered was tracking station location (10 foot spherical, excepting master station longitude). Since all satellites fall into a single inclination, period, and near circular eccentricity, the geopotential model can be a very simple one, with higher order terms folded back on lower order terms. By solving for a model appropriate to this orbit, in an off-line environment, the effects of geopotential errors are negligible. This overall simulation approach is shown in Figure 8-3

The simulation results are presented in Figures 8-4 and 8-5. For a detailed analysis of the results see Part II, Report C-9. Both processing concepts are capable of meeting design goals on UERE in the twelve-foot range.

6.0 DATA FILTERING CONCEPTS

The purpose of the linear filter is to obtain an optimal estimate of a state vector, x, which is observed at discrete times, t_k. The dynamics of the problem relate x at different times by the process:

$$x(k+1) = \Phi(k) + w(k) \tag{1}$$

where

$\Phi(k)$ is the state transition matrix from t_k to t_{k+1}

and

$w(k)$ is a purely random Gaussian vector with zero mean due to process noise.[1]

The observation equation is

$$z(k) = H(k)\, x\,(k) + v(k)$$

where

$H(k)$ is the sensitivity matrix (partial derivatives of the observations, z, with respect to the state)

and

$v(k)$ is another purely random Gaussian vector with zero mean due to observation noise.

Also, w(k) and v(k) are assumed to be independent.

The literature provides three comparative analyses (Reference 1, 2, 3) of alternative filter formulations available. Those that were considered most applicable to GFS requirements include:

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[1] Reference 3 considers the process noise to be in variables other than the state vector. While this causes slightly more computation in the time update, the statistical effect is the same.

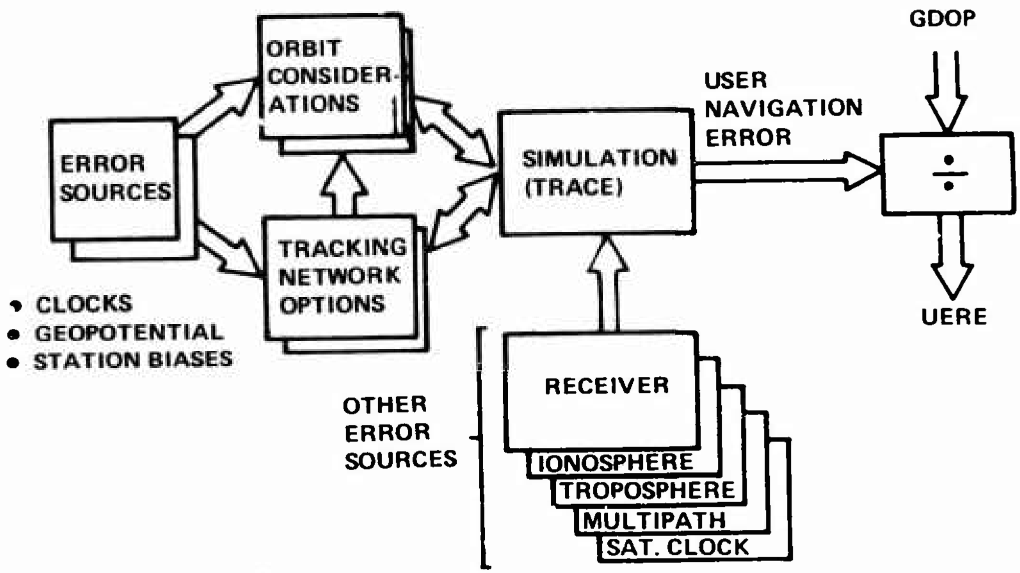

Figure 8-3 Simulation

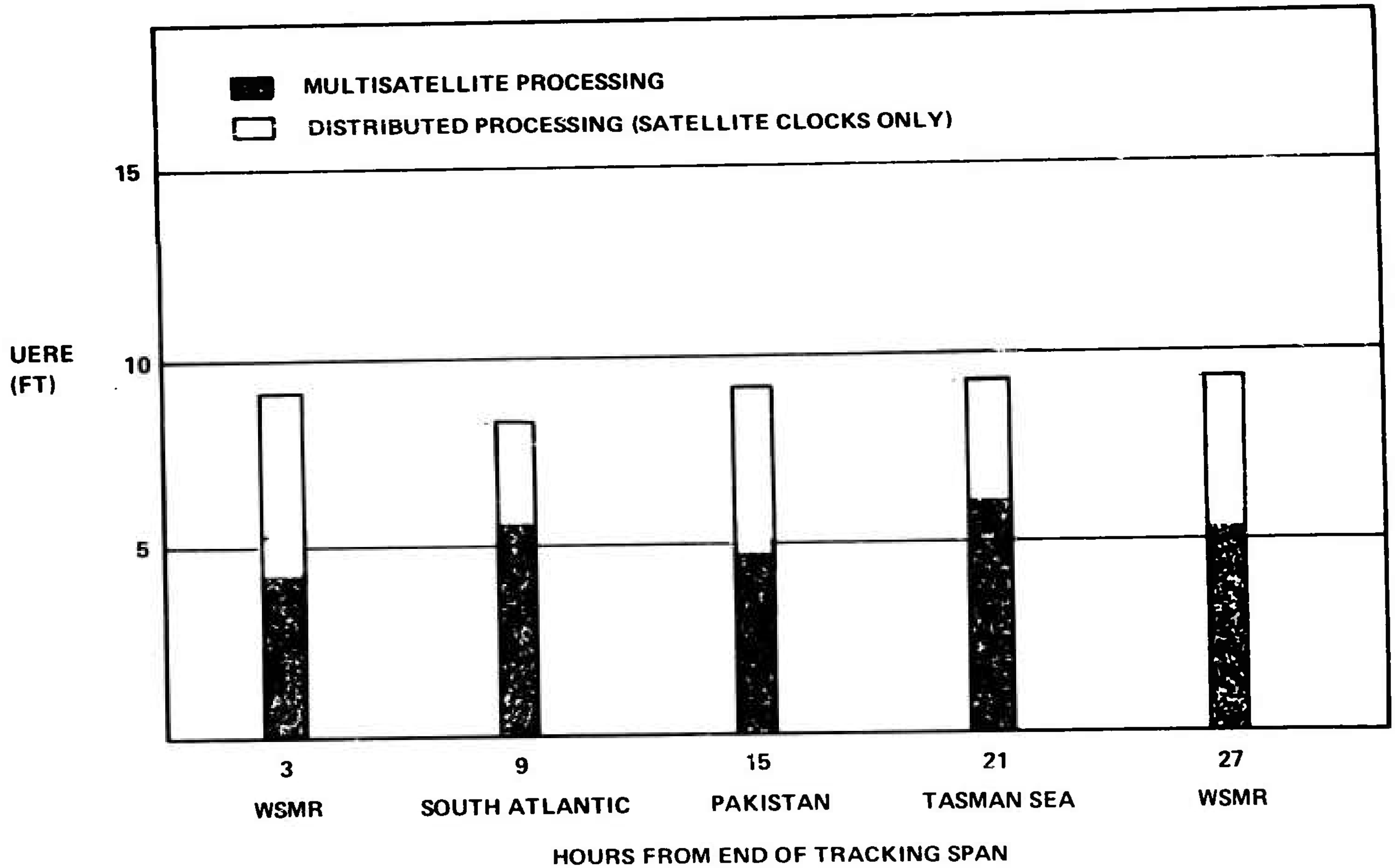

Figure 8-4 User Equivalent Range Errors (With 10 Foot Spherical Station Errors)

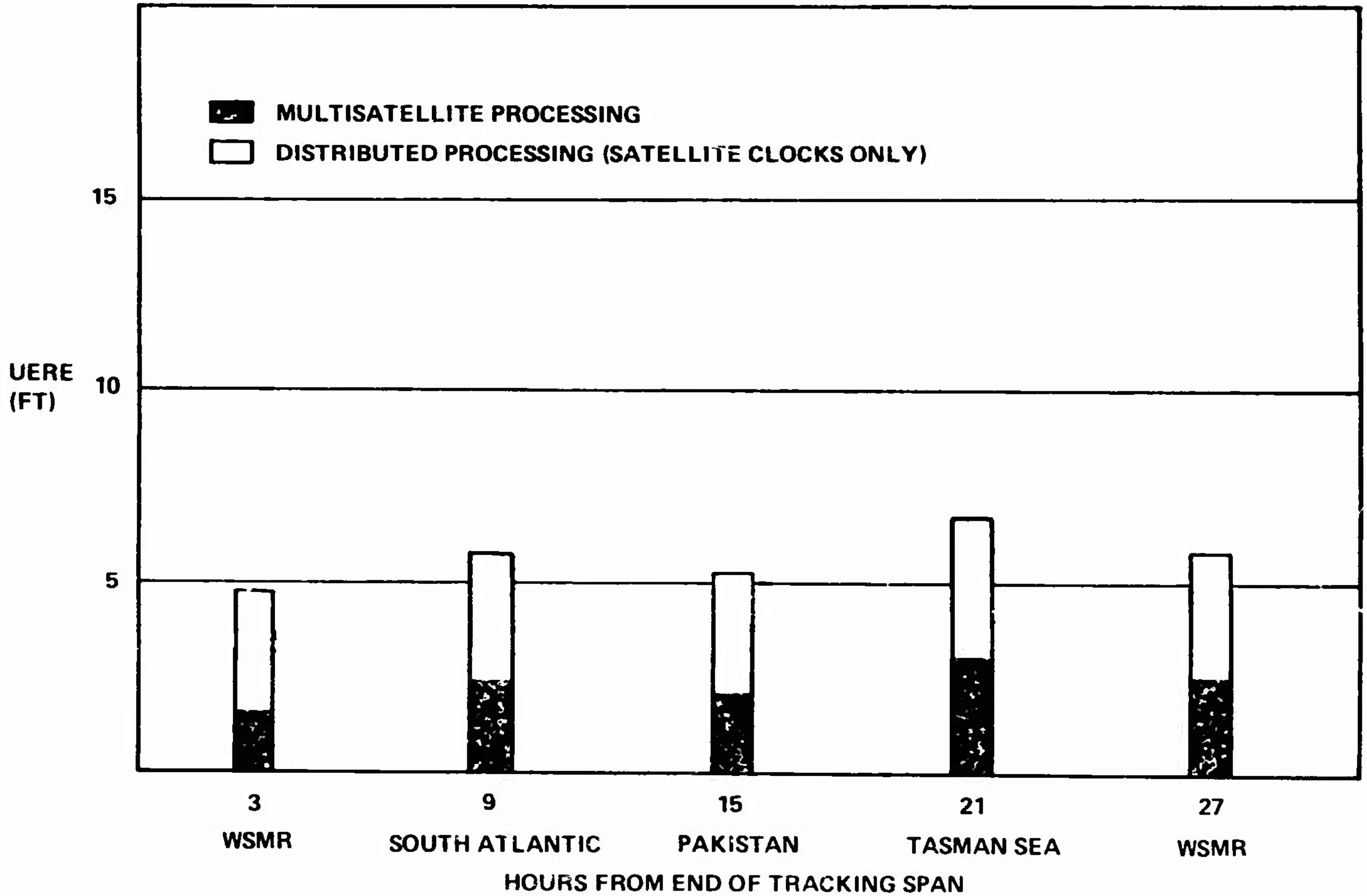

Figure 8-5 User Equivalent Range Errors (Without Sensor Location Errors)

- <u>Kalman Filter</u>

The Kalman Filter updates the covariance matrix of the state vector by*

$$P(k) = \varphi(k)\, P(k-1)\, \varphi^T(k) + Q(k)$$

where Q(k) is the covariance matrix of the process noise.

The state vector is update by Equation (1), i.e.,

$$x(k) = \varphi(k)\, x(k-1)$$

and corrected by

$$x^+(k) = x(k) + K\, [z(k) - H(k)\, x(k)]$$

where the Kalman gain matrix is

$$K = P(k)\, H^T(k)\, [H(k)\, P(k)\, H^T(k) + R(k)]^{-1}$$

and where R(k) is the covariance matrix of the observation noise V(k).

The covariance matrix incorporates the new observation by

$$P^+(k) = P(k) - KH(k)\, P(k)$$

- <u>Stabilized Kalman Filter</u>

The last equation is modified to

$$P^+(k) = [I - K\, H(k)]\, P(k)\, [I - K\, H(k)]^T + K\, R(k) K^T$$

where I is the identity matrix of appropriate rank. This modification essentially preserves the symmetrical properties of P(k), makes the filter less susceptable to numerical roundoff, and allows the filter to generate correct covariances regardless of the degree of optimality of K.

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*Notation is continued from main text. Superscript T denotes the transpose; negative superscript denotes the inverse of the matrix; plus superscript denotes a value after measurement incorporation.

- Square Root Filters

Square root estimators attempt to achieve the same degree of numerical stability as the stabilized Kalman but with fewer computational penalties.

The differences in the square root formulations occur in the incorporation of the measurements. The index k, relating to the measurement at t_k, will henceforth be omitted.

- Potter Square Root Filter

The square root of the covariance is defined by

$$SS^T = P$$

This is used to compute

$$f = S^T H$$

For one measurement

$$\alpha = r + f^T f$$

where r is the variance of the measurement (corresponding to R above)

$$\gamma = 1/(\alpha + \sqrt{\alpha}\, r)$$

$$b = Sf$$

$$S^+ = S - \gamma b f^T$$

$$x^+ = x + \frac{b}{\alpha} (z - Hx)$$

- **Andrews Square Root Filter**

For more than one measurement

$$UU^T = R + f^T f$$

$$S^+ = S - SfU^{-T} (U + G)^{-1} f^T$$

where the square foot of the measurement covariance matrix is defined by

$$GG^T = R$$

$$x^+ = x + Sf(UU^T)^{-1} (z - Hx)$$

- **Carlson Triangular Formulation**

Carlson picks an upper triangular root for the matrix which updates S

$$S^+ = SA$$

$$A \triangleq [I - ff^T/\alpha]^{\frac{1}{2}}$$

This matrix is found by Cholesky decomposition. The algorithm is given explicitly in Appendix B of Reference 2.

The candidates considered by Gura and Bierman (Reference 1) include:

a) the Kalman filter with updating only after a group of ν observations.

b) the stabilized Kalman filter attributed to Joseph in Reference 2.

c) Sequential Least Squares

d) Potter Square Root

e) Bellantoni and Dodge Square Root (this is not considered here since it requires a time consuming computation of eigenvalues), and

f) Andrews Square Root

Finally, G. J. Bierman (Reference 3) considers

a) Kalman (Covariance Filter)

b) Sequential Least Squares (Information Filter)

c) Covariance Square Root

d) Information Square Root

These names are rather descriptive but (c) is shown to be equivalent to Potter (d above) yet is called Householder update while (d) is called "Potter update". Finally, in Table VII of Reference 3 among several other misprints, "Potter" and "Householder" are obviously interchanged. "Potter" seems to mean the RSS formulation of Reference 2.

The following scenario was assumed in using the formulas of the references to evaluate the above linear filters in terms of their relative operation and storage requirements: 100 well-distributed single observations on each satellite in twelve hours. All counts will be per satellite.

Reference 1 ignores add instructions, assuming that the total instruction count will be proportional to the result thus obtained. Table 8-1 gives the number of multiples from the formulas of Reference 1, assuming that process noise is not accounted for. Table 8-1 shows also the same counts from Reference 2. Where comparative values are available, the agreement between these references is excellent.

The application of process noise is assumed to be applied between batches of observations in Reference 1. This is in conflict with the assumption of well distributed single observations made above. In the GPS there may be data gaps which could be used to define batches, yet "deweighting" only between the last observation before the data gap and the first observation after the gap (and not during the batch) is not strictly correct. Nevertheless, this assumption was made in Reference 1 because to do other wise would increase the computational cost tremendously. Reference 2 seems to make a similar assumption. The added computation then will amount to a few hundred multiples except in the Kalman filters. The Kalman filters can incorporate an additive deweighting matrix without any multiply instructions.

The effect of the process noise computation at every observation time is shown in Table 8-2. It is assumed that the covariance matrix is only updated once per batch. The apparent contradiction is resolved when it is remembered that the state vector for orbit determination consists of corrections to epoch parameters. Furthermore, satellite positions are obtained from ephemerides which are not changed during a batch. The basic data for Table 8-2 comes from Reference 2 except that the additional formulation count for the Potter square Root Filter was taken from Reference 1.

The tables indicate that the Carlson Triangular formulation is preferable when no process noise is present (except when least-squares can be used). It must be preferred to the Standard Kalman filter on the basis of numerical stability. It should be pointed out that no advantage from partitioning (See Reference 2, Equations 31 and 32) was assumed. The published algorithm in Reference 1, treats each observation as an independent measurement.

Formulas for storage requirements are also given in Reference 1 and Appendix B. When the number of state variables is much larger than the number of observables at one time point (as in GPS) the ranking is

Least	-	Kalman (Standard and Stabilized)
Middle	-	Square-Root Filters
Most	-	Least Squares

Additional analysis of these filtering concepts may be found in Appendix B. These factors, and the analysis of Appendix B, tend to suggest that the sequential least squares algorithm with deweighting between batches to account for process noise is the most efficient for GPS applications. However, due to the fact that process noise in the GPS is expected to contain higher frequency components due to clock state noise, the Carlson recursive estimator was chosen over batch least squares because of its added flexability in handling such processes and over the Kalman because of its superior numerical stability. The baseline orbit support system, described in Section 7.0, will thus utilize a Carlson Square Root estimator for both ephemeris and clock state estimation.

Ref. 1 Gura and Bierman "Computational Efficiency of Linear Filtering Algorithms," Aerospace TR 0059(6521-01)-1.

Ref. 2 Carlson "Fast Triangular Formulation of the Square Root Filter," AIAA Journal, Sept. 1973.

Ref. 3 Bierman, G. J. "A Comparison of Discrete Linear Filtering Algorithms," IEEE Transactions on Aerospace & Electronic Systems, AES-9, Jan. 1973.

TABLE 8-1

MULTIPLICATIONS EXECUTED

(No Process Noise)

Method	Reference 1	Reference 2
Standard Kalman	23,050	23,880
Stabilized Kalman	186,550	188,150
Least Squares	13,500	Not Available
Potter Square Root	37,300	36,877
Andrews Square Root	37,900	Not Available
Carlson Triangular	Not Available	23,313

TABLE 8-2

EQUIVALENT MULTIPLICATIONS EXECUTED

(With Process Noise)

Method	
Standard Kalman	23,880
Stabilized Kalman	188,150
Potter Square Root	91,750
Carlson Triangular	82,713

7.0 BASELINE ORBIT-SUPPORT RECOMMENDATION

Previous sections have described two candidate ephemeris and clock model determination concepts and have compared these in terms of accuracy, legacy, and cost/schedule risk. Based upon these analyses, the distributed processing concept, in which both satellite and ground clock states are estimated, has been adopted for the baseline configuration. This concept also lends itself readily to the utilization of external (GFE) software and computer resources to accomplish those functions normally requiring "big" computers, eg., calibration, ephemeris integration, and computation of an ephemeris of state transition matrices (or "partials"). By proposing the consideration of GFE computational and intellectual resources available at NWL, particularly during the demonstration phase, the remaining GPS orbit support tasks can be accomplished on small scale computers, with small non-recurring investment and excellent legacy.

This proposed baseline is shown in Figure 8-6. Three functions are involved:

- Off-Line Calibration Processor: A program such as CELESTE to produce ephemerides and state partials (state transitions), and to provide calibration support in sensor locations. refraction modeling, and (possibly) a priori clock state models. Greater operational flexibility is afforded by the ability to produce these reference ephemerides over extended time periods, to a level of precision (tentatively 1500 meters) where the linearity of the process will permit non-iterative on-line filtering techniques and ephemeris updating through the state transition matrix. (To accomplish this extended precision goal, the calibration process should extend to such areas as geopotential modeling with satellite altitude.) This processing support can be absorbed within the GPS program as the system matures.

- <u>On-Line Ephemeris Correction Processor</u>: A program which cyclically updates the reference ephemerides, one-by-one, utilizing range-difference* data. The baseline has been modeled after the program MUSTANG (a subroutine in FORD, the AOES prototype) utilized for similar ephemeris improvement applications in force model studies, satellite accelerometer data reduction, etc. Extensive experimentation with MUSTANG, utilizing range difference data and several filter concepts, has been undertaken to evaluate sizing, speed and accuracy.

- <u>On-Line Clock Calibration Processor</u>: A program which updates the states of all clocks (except reference clock), utilizing pseudo-range data and the updated ephemerides. Considering offset and rate as clock model states to be estimated, the total number of solution parameters will not exceed 60 for the full-matured system.

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* While range difference data from all stations will meet the Phase I specifications on ephemeris contribution to UERE, the application of ranging data from one of the stations (preferably Alaska) provides improved world-wide distribution of UERE, and the baseline incorporates this data type. The processing concept remains distributed, insofar as the Ephemeris processing is concerned; in the Ephemeris processing the satellite clock parameters are also estimated, relative to the (master) clock at the station for which ranging data are processed. Simulation data presented earlier (Figure D and E) for the distributed concept is modelled against this baseline.

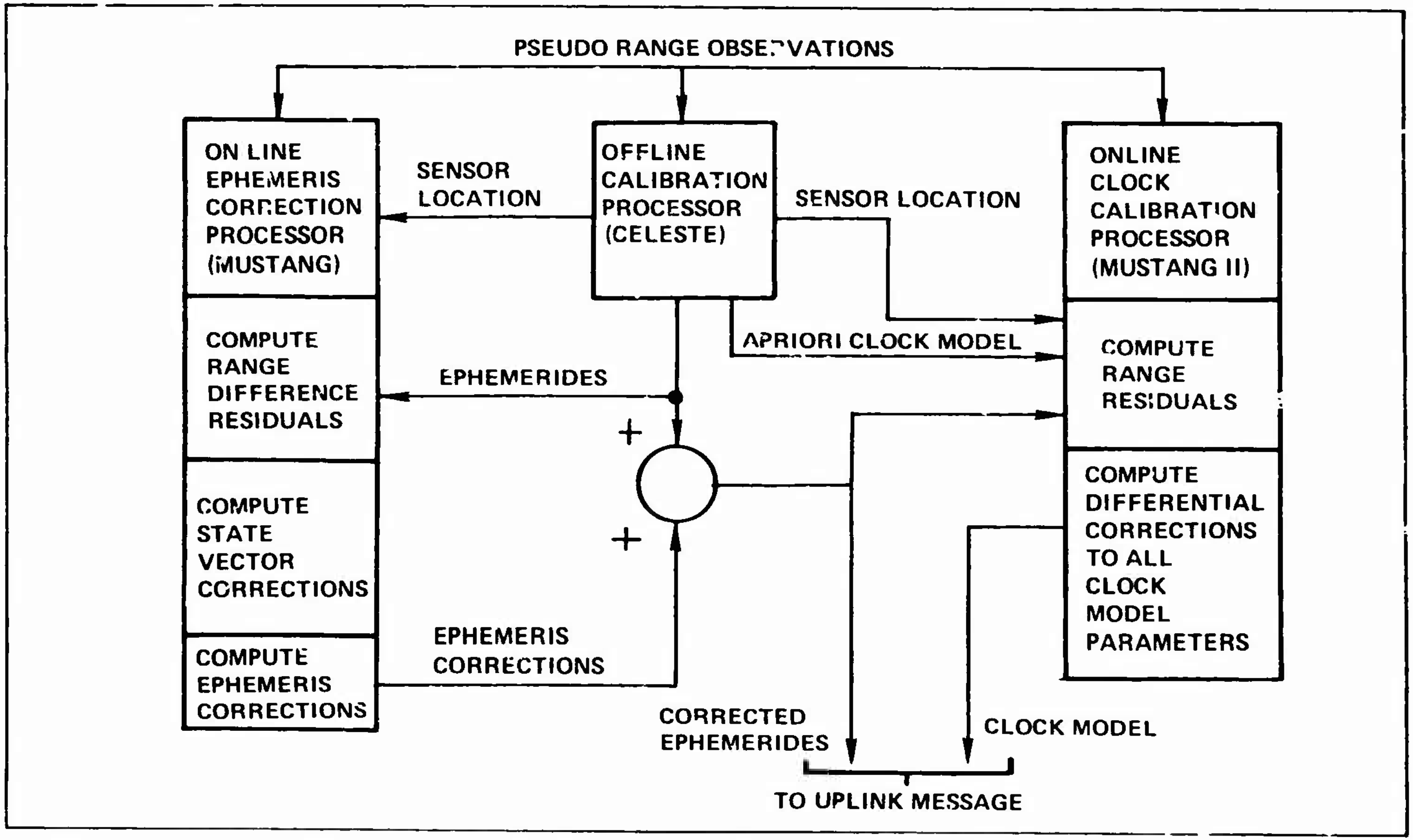


Figure 8-6 Distributed Processing Ephemeris Determination Concept

REPORT C-8

APPENDIX A

CORRECTOR SIMULATIONS

Corrector Simulations

Simulation results of the corrector using the Kalman estimator have been obtained during Δ-testing of orbital element corrections. Six cases are presented where a 3 x 10^{-5} error introduced into one of the elements was successfully removed by the corrector.

Ranges were computed over 15 days at one-hour intervals to two stations located 14°N, -145°W and 22°N, 158°W. These simulated observations were forced to reflect a 0.3 meter standard deviation in the ranges. A priori statistics to the Kalman filter were 10^{-14} for the mean motion solution parameter and 10^{-10} for all of the other FG elements.

The force-models considered throughout included a 12th-order geopotential, the gravitational attraction of the sun and the moon and the solar radiation pressure. The radiation pressure parameter adopted was 0.084 cm^2/gm.

Table 1 lists the initial values of the nominal orbital elements and the number of observations simulated over the 15-day fit-span.

TABLE 1. ORBITAL ELEMENTS

Satellite	a(e.r.)	e	i(deg)	Ω(deg)	ω	L_o(deg)	# Obs
A	4.172	10^{-4}	63	165	0	285	264
B	4.172	10^{-4}	63	285	0	165	256
C	4.172	10^{-4}	63	45	0	45	259

Range differences, obtained by differencing successive ranges, were the observations. In Table 2 are presented the ephemeris errors in meters

TABLE 2

EPHEMERIS ERRORS (Meters) BEFORE AND AFTER CORRECTION WITH KALMAN FILTER

SATELLITE	$3x10^{-5}$ ERROR	MAXIMUM		MEAN		RMS	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
A	a_F	1574	5	1233	1.7	1264	1.9
A	a_G	1593	1.8	1233	1.0	1263	1.0
A	X	1317	0.6	1039	0.4	1065	0.4
B	a_F	1567	3.2	1230	0.8	1262	1.0
B	a_G	1593	1.8	1232	1.0	1263	1.0
C	a_F	1601	2.6	1231	1.2	1262	1.4

between the "time" ephemeris and the uncorrected ephemeris and between the "true" ephemeris and the corrected ephemeris. This analysis also demonstrates the linear quality and stability of the error growth rate over 15 days.

Sensitivity tests were conducted on satellite C where the only force-model considered was the geopotential. Range observations were simulated at 15-minute intervals from five stations located at (58°N, 152°W), (14°N, -145°W), (22°N, 158°W), (35°N, 121°W) and (43°N, 71°W). The range observations were made to represent a standard deviation error of 1 meter.

Differences were computed between ephemerides generated with a full 12th-order geopotential and ephemerides obtained with the geopotential function truncated to a lower order. Two cases are presented, one, for a truncated 6th-order geopotential where the harmonics ignored produce no errors, that is, where the standard deviation from the ephemeris errors over 3600 minutes is 0.05 meters (less than the observations' 1 meter); the other case is a truncated 4th-order geopotential where the errors between ephemerides computed before and after correction have been reduced as follows:

ERROR	BEFORE	CORRECTED
	(METERS)	
Maximum	9.0	3.6
Mean	2.9	1.9
RMS	3.7	2.0
σ	2.3	0.7

The results are presented graphically in Figures 1 and 2 showing radial (U), in-track (V), and cross-track (W) errors remaining over fit-intervals of

1 day (184 range observations), 1½ days (254 observations), and 2 days (363 observations) each followed by a 12-hour prediction period.

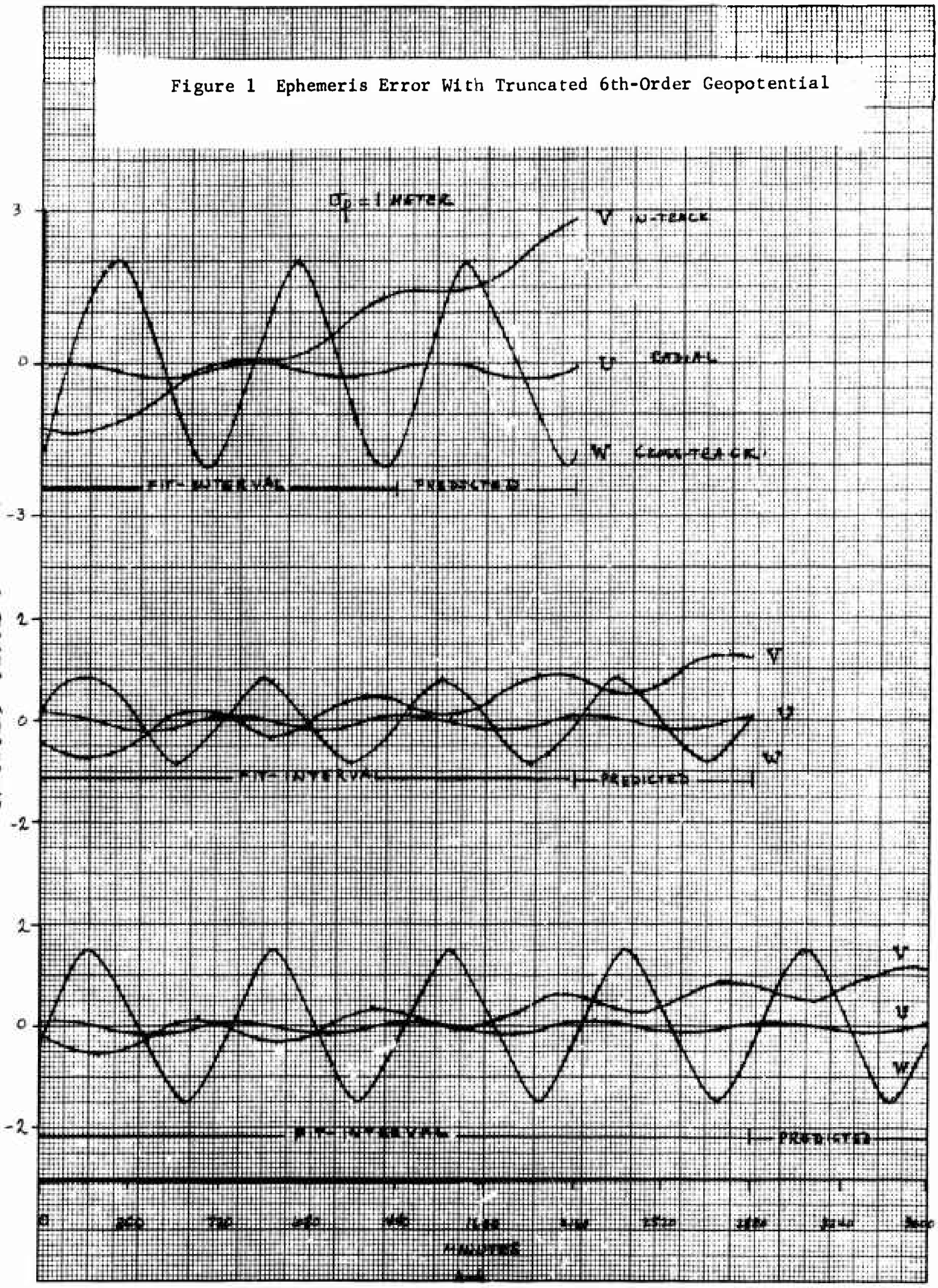
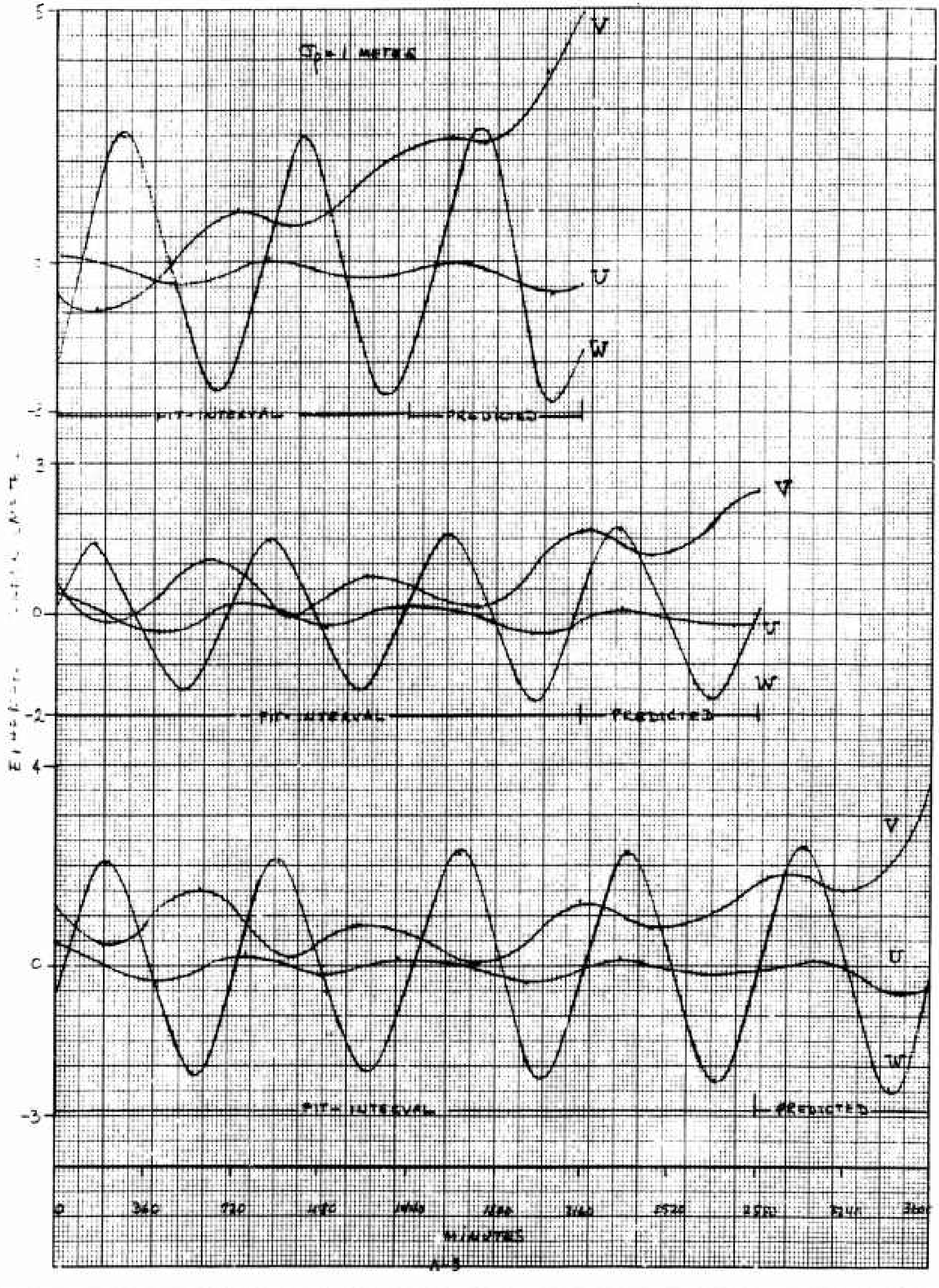


Figure 1 Ephemeris Error With Truncated 6th-Order Geopotential

Figure 2 Ephemeris Errors With Truncated 4th-Order Geopotential



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APPENDIX B

ADDITIONAL FILTER ANALYSIS

Summary

A trade study concerning several alternative concepts and implementation techniques for the online operational ephemeris determination and clock calibration functions was performed. The alternatives considered were first a distributed processing concept utilizing a corrector technique for orbit determination in the form of MUSTANG or CELESTE, a non-corrector technique in the form of TRACE sequential batch least squares or AOES, and a multisatellite clock calibration process utilizing sequential batch or a recursive filter.

The second processing concept consisted of a simultaneous multisatellite orbit determination and clock calibration process utilizing a sequential batch corrector, recursive corrector, or TRACE sequential batch non-corrector.

The recursive filter algorithms that were evaluated were

- standard Kalman
- stabilized Kalman
- Potter square root and
- Andrews square root

At the time this analysis was conducted, the Carlson triangular filter was not under consideration. As discussed in Report C-8, however, this filter is competitive with the standard Kalman in terms of computational requirements yet has superior numerical stability.

All alternative concepts/processes were compared with each other using the following criteria:

- computational requirements
- accuracy
- cost
- technical risk
- legacy

The corrector processes are differentiated from the non-corrector processes by the fact that they are non-iterative processes which compute corrections to an existing or "reference" ephemeris and do not require numerical integration of vehicle orbits online.

The results of this effort and recent simulations indicate that the distributed corrector process is the preferred approach yielding user accuracies which are nearly equivalent to those of the simultaneous process.

Within the distributed concept/corrector process, MUSTANG and CELESTE should be virtually equivalent to each other except in software development costs and the proven capability subcategory of technical risk. For this reason, MUSTANG is recommended over CELESTE for orbit determination.

As for clock calibration, the sequential batch estimator is preferred over the recursive estimator primarily on the basis of computational efficiency. Although the recursive estimator would be more flexible in modeling non-stationary measurement noise and clock state noise the amount of additional accuracy that would be obtained if this were done properly is somewhat in question. Also, although the sequential batch estimator does not allow a practical application of clock state noise within a data batch, it does allow a pseudo application of it between batches in the form of batch deweighting.

Filter Equations

System Model

The equations used in the sequential batch and recursive estimators are based upon a linear system model of the form

$$(1) \qquad \underline{X}\,(k+1) = \phi(k,k+1)\,\underline{X}\,(k) + \underline{r}\,(k+1)$$

$$(2) \qquad \underline{Y}\,(k+1) = M\,(k+1)\,\underline{X}\,(k) + \underline{w}\,(k+1)$$

where

$\underline{X}\,(k+1)$	=	An (n x 1) vector which describes the system state at time t_{k+1}
$\underline{X}\,(k)$	=	An (n x 1) vector which describes the system state at time t_k
$\phi(k,k+1)$	=	The state transition matrix
$\underline{Y}\,(k+1)$	=	An (m x 1) vector of observations taken at time t_{k+1} which are linearily related to the system state vector at time t_{k+1} through the "measurement matrix" M (k+1)

$\underline{r}$ (k+1) = an (n x 1) vector of "state noise" processes which reflect random disturbances acting on the system state

w(k+1) = an (m x 1) vector of "measurement noise" which reflect errors in the observations

The statistics of $\underline{r}$ and $\underline{w}$ are assumed to be known and given by

$$E\{\underline{r}\} = E\{\underline{w}\} = 0 \tag{3}$$

$$E\{\underline{r}(k)\,\underline{r}(j)^T\} = \begin{cases} 0 & \text{if } k \neq j \\ R(k) & \text{if } k = j \end{cases} \tag{4}$$

$$E\{\underline{w}(k)\,\underline{w}(j)^T\} = \begin{cases} 0 & \text{if } k \neq j \\ W(k) & \text{if } k = j \end{cases} \tag{5}$$

where $E\{\ \}$ is the expected value operator, R(k) is the covariance matrix of $\underline{r}$, and W(k) is the covariance matrix of $\underline{w}$. Equation (3) indicates that $\underline{r}$ and $\underline{w}$ are assumed to have zero mean whereas equations (4) and (5) assume that $\underline{r}$ and $\underline{w}$ are uncorrelated in time. Although these assumptions at first seem to be quite presumptuous, further analysis indicates that they are not. For example if the observations contain biases and have time correlated random errors, equations (3) through (5) can still be satisfied by adding the observation biases and correlated portions of the measurement noise to the system state vector. Similarly for the vector of state noise processes.

The assumption of system linearity also justifies comment. Although the GPS is by no means a linear dynamical system, linear filtering techniques can still be utilized. This is due to the fact that the actual algorithms being considered here are in reality first order expansions about a priori states.

In the TRACE sequential batch algorithm for example, differential correction techniques are exploited which are basically linearizations of the system state about some a priori or "first quess" state. Corrections to the initial state are obtained by weighting residuals between observations predicted from a trajectory generated with this initial state and those actually observed. These corrections are then added to the initial state, a new trajectory generated, and the entire process repeated until either the correctors are less than some prespecified tolerance or the residuals are below some acceptable level.

For the corrector process, again corrections are estimated for an initial state vector. However, here the corrected initial state vector is not used to generate a new trajectory. An a priori or "reference" ephemeris is available for the entire observation interval in addition to times beyond the observation interval. Thus only corrections to the reference ephemeris are estimated and these corrections are then algebraically summed with the reference to define a new ephemeris. The process is non-iterative and requires no trajectory integration during the filtering process.

Recursive Estimators

Standard Kalman

The standard Kalman equations are given by

(6) $\hat{\underline{X}}(k+1/k) = \phi(k+1,k)\ \hat{\underline{X}}(k/k)$

(7) $P(k+1/k) = \phi(k+1,k)\ P(k/k)\ \phi(k+1,k)^T + R(k)$

(8) $B(k+1) = P(k+1/k)\ M^T(k+1)\left[M(k+1)\ P(k+1/k)\ M(k+1)^T + W(k+1)\right]^{-1}$

(9) $\hat{\underline{X}}(k+1/k+1) = \hat{\underline{X}}(k+1/k) + B(k+1)\left[\underline{Y}(k+1) - \hat{\underline{Y}}(k+1/k)\right]$

(10) $\hat{\underline{Y}}(k+1/k) = M(k+1)\ \hat{\underline{X}}(k+1/k)$

(11) $P(k+1/k+1) = \left[I - B(k+1)\ M(k+1)\right]\ P(k+1/k)$

where

$\hat{\underline{X}}(k+1/k)$ = estimate of the system state vector for time t_{k+1} based upon data through time t_k (predicted state)

$\hat{\underline{X}}(k/k)$ = estimate of the system state vector for time t_k based upon data through time t_k

$P(k+1/k)$ = a priori covariance matrix of the system state vector for time t_{k+1} predicted from time t_k

$B(k+1)$ = measurement weighting matrix at time t_{k+1}

$\hat{\underline{Y}}(k+1/k)$ = predicted measurement vector for time t_{k+1} from data through time t_k

$P(k+1/k+1)$ = covariance matrix of system state vector at time t_{k+1} based upon data through time t_{k+1}

Stabilized Kalman

The stabilized Kalman is identical to the standard Kalman except that equation (11) is replaced with

(12) $P(k+1/k+1) = C(k+1)\ P(k+1/k)\ C(k+1)^T + B(k+1)\ W(k+1)\ B(k+1)^T$

where

(13) $C(k+1) = I - B(k+1)\ M(k+1)$

Replacing (11) with (12) essentially preserves the symmetrical properties of P(k), makes the filter less susceptable to numerical roundoff and allows the filter to generate correct covariances regardless of the degree of optimality of the filter weighting matrix B(k).

Potter Square Root

The Potter square root algorithm attempts to achieve the same degree of numerical stability as the stabilized Kalman estimator but with fewer computational penalties. The equations are

(14) $$\hat{\underline{X}}(k+1/k) = \phi(k+1/k)\,\hat{\underline{X}}(k/k)$$

(15) $$\sqrt{P(k+1/k)} = \left\{[\phi(k+1,k)\sqrt{P(k+1/k)}][\phi(k+1,k)\sqrt{P(k+1/k)}]^T + R(k+1)\right\}^{\frac{1}{2}}$$

$$= \left\{\phi(k+1,k)\,P(k+1/k)\,\phi(k+1,k)^T + R(k+1)\right\}^{\frac{1}{2}}$$

(16) $$G(k+1)^{-1}M(k+1) = (\beta_1, \beta_2, \ldots, \beta_m)^T$$

(17) $$G(k+1)^{-1}\underline{Y}(k+1) = (\theta_1, \theta_2, \ldots, \theta_m)^T$$

where

(18) $$W(k+1) = G(k+1)\,G(k+1)^T$$

The above m observations are then processed as follows

(19) $$\tilde{\underline{X}}_1 = \hat{\underline{X}}(k+1/k)$$

(20) $$Q_1(k+1) = \sqrt{P(k+1/k)}$$

(21) $$S_i = Q_i^T \beta_i$$

(22) $$a_i = S_i^T S_i + 1$$

(23) $$Q_{i+1} = Q_i - Q_i S_i \left[S_i^T / (a_i + \sqrt{a_i})\right]$$

(24) $$\tilde{\underline{X}}_{i+1} = \tilde{\underline{X}}_i + Q_i S_i \left[(\theta_i - \beta_i^T \tilde{\underline{X}}_i)/a_i\right]$$

$$\left.\vphantom{\int}\right\} \quad i = 1,2,\ldots m$$

(25) $$\sqrt{P(k+1/k+1)} = Q_{m+1}$$

(26) $\quad \hat{\underline{X}}(k+1/k+1) = \tilde{\underline{X}}_{m+1}$

Andrews Square Root

The Andrews square root formulation is a direct decomposition of the standard Kalman. The equations are easily derived by replacing the covariance matrix P in the standard Kalman equation with its square root $\sqrt{P}$ defined by

(27) $\quad \sqrt{P}\,(\sqrt{P})^T = P$

For example, equation (8)

$$B(k+1) = P(k+1/k)\,M^T(k+1)\left[M(k+1)\,P(k+1/k)\,M(k+1)^T + W(k+1)\right]^{-1}$$

becomes

(28) $\quad B'(k+1) = \sqrt{P}\,(\sqrt{P})^T M^T \left[M\sqrt{P}\,(\sqrt{P})^T M^T + W\right]^{-1}$

$$= \sqrt{P}\,Z\,(Z^T Z + W)^{-1}$$

The equations are

(29) $\quad \hat{\underline{X}}(k+1/k) = \phi(k+1,k)\,\hat{\underline{X}}(k/k)$

(30) $\quad \sqrt{P(k+1/k)} = \left\{\left[\phi(k+1,k)\sqrt{P(k+1/k)}\right]\left[\phi(k+1/k)\sqrt{P(k+1/k)}\right]^T + R(k+1)\right\}^{\frac{1}{2}}$

(31) $\quad W = GG^T$

(32) $\quad Z = \left[\sqrt{P(k+1/k)}\right]^T M(k+1)^T$

(33) $\quad UU^T = W + Z^T Z$

(34) $\quad \sqrt{P(k+1/k)} = \sqrt{P(k+1/k)} - \sqrt{P(k+1/k)}\;Z\,(U^T)^{-1}\,(U+G)^{-1}\,Z^T$

(35) $\quad \hat{\underline{X}}(k+1/k+1) = \hat{\underline{X}}(k+1/k) + \sqrt{P(k+1/k)}\;Z\,(UU^T)^{-1}\left[\underline{Y}(k+1) - \hat{\underline{Y}}(k+1/k)\right]$

(36) $\quad \hat{\underline{Y}}(k+1/k) = M(k+1)\,\hat{\underline{X}}(k+1/k)$

Sequential Batch Least Squares

The sequential batch least squares estimator is a non-recursive estimator due to the fact that it processes data batches to obtain one state vector update per data batch whereas the recursive estimators obtain a state vector update after processing either a single observation or an observation vector. The other significant difference is the inability of the sequential batch estimator to handle state noise within a data batch. That is the system model is assumed to be perfect within the batch. However, if the data batch does not cover a larger dynamical time span than is accurately described by the system model, no problem should occur provided deweighting between batches is performed.

The equations for the sequential batch estimator are

$$(37)\quad P(o/Lv)^{-1} = P(o)^{-1} + \sum_{i=}^{L-1} \phi^T(jv+1, o) \left[\sum_{i=jv+1}^{jv+v} M_i^T W^{-1} M_i \right] \phi(jv+1, O)$$

$$(38)\quad P(Lv/Lv) = \phi\left[(L-1)\, v + 1, o\right] P(o/Lv)\, \phi^T \left[(L-1)\, v + 1, o\right]$$

$$(39)\quad \hat{\underline{X}}(Lv/Lv) = \phi\left[(L-1)\, v + 1, o\right] \left\{ \underline{X}(o) + P(o/Lv) \sum_{j=o}^{L-1} \phi^T (jv+1, o) \left(\sum_{i=jv+1}^{jv+v} M_i^T W^{-1} \left[\underline{y}(i) - \hat{\underline{y}}(i/o) \right] \right) \right\}$$

$$(40)\quad \hat{\underline{y}}(i/o) = M(i)\, \phi(jv+1, o)\, \hat{\underline{X}}(o)$$

where v is the number of data vectors used in each state vector update and L is the number of updates. $P(o)$ and $\underline{X}(o)$ are respectively the covariance matrix of the estimate and the estimate obtained from the previous data batch.

Assumptions About the Implementation Alternatives

In comparing the several concepts and alternatives, assumptions had to be made concerning the basic nature of each process. These were

- MUSTANG - a corrector process which computes corrections to a reference ephemeris obtained from an off site facility such as the Naval Weapons Laboratory (NWL). This could utilize either a sequential batch or a recursive estimator to compute these corrections.

- CELESTE - essentially the same as MUSTANG in its processing concept except that the corrector portion is a subset of the complete program since in its present configuration it contains a package for reference ephemeris generation.

- TRACE sequential batch - an iterative differential correction process that requires trajectory integration at each iteration.

- AOES - essentially a sequential batch or batch process similar to TRACE but with limited accuracy and flexability.

Computation Requirements/Sequential Batch Estimator vs Recursive Estimator

In order to obtain a feel for the number of computations required by the sequential batch and recursive algorithms, operation and storage totals were computed for each one assuming several methods of implementation. Also, to obtain a feel for the growth of these requirements as the Global Positioning System (GPS) matures, these totals were obtained for each phase of the program.

In order to accomplish this, several assumptions also had to be made about the ground system configuration and the data collection rate for each phase. The following summarizes these assumptions:

Phase I

- 4 space vehicles
- 28 orbit determination parameters (7 per vehicle)
- 14 clock parameters (2 per vehicle, 2 per monitor station)
- 4 ground stations

Phase II

- 9 space vehicles
- 63 orbit determination parameters
- 24 clock parameters
- 4 ground stations

Phase III

- 24 space vehicles
- 168 orbit determination parameters
- 56 clock parameters
- 5 Ground Stations

During a 24 hour period, there will be two passes for each vehicle over all ground stations and the average pass duration will be 240 minutes. Although not all vehicles are seen by all stations twice a day, this assumption simplifies the analysis without significantly affecting the results. Also, the assumption of equal length passes of 240 minutes is not quite true, but averaged over 24 hours the net effect of this differences is again not significant. The data rate was assumed to be one smoothed sample every 15 minutes during a visibility period.

The equations used to generate operation and storage counts for these algorithms were obtained directly from reference 1. They exploit matrix symmetry where possible and assume that a priori and aposterori filter elements share common storage locations. Also, matrix inversion when performed, is assumed to be accomplished by Cholesky factorization. The equations used are reproduced in TABLES A, B and C for convenience. In these equations, the following definitions apply:

L = number of dynamical updates in the interval of comparison

M = number of observations received at one time

N = number of state variables updated

V = number of data vectors of length M received between system updates

Q = number of multiplications required for square root extraction (assumed to be 7)

It must be mentioned here that these equations only represent the number of operations (primarily multiplications) required to cycle the filter equations and do not reflect those operations which are required to obtain the transition matrix ϕ, to compute the measurement sensitivity matrices M, or to handle bookkeeping requirements. Likewise, the storage counts only reflect the storage required by the filter equations and their respective data.

TABLE A - OPERATION TOTALS WITHOUT STATE NOISE

STANDARD KALMAN	$\left[(1.5N^2 + 3.0N + 0.5M^2 + 1.5M + q + 1.5\,NM)\,MV + 1.5N^3 + 1.5N^2\right] L$
STABILIZED KALMAN	$\left[(1.5N^3/M + 0.5N^2/M + 0.5M^2 + 1.5M + q + 2.5N^2 + 2.5NM + 3.0N)\,MV + 1.5N^3 + 1.5N^2\right] L$
SEQUENTIAL BATCH	$\left[(MN + 0.5N^2 + 2.5N)\,MV + 1.5N^3 + 2.5N^2\right] L + 2.5N^3 + 4.5N^2 + 2.0NQ$
POTTER SQUARE ROOT	$\left[(3.0N^2 + 4.5N + q + 1.5 + 0.5M)\,MV + N^3 + N^2\right] L$
ANDREWS SQUARE ROOT	$\left[(3.0N^2 + 1.5NM + 3.5N + 0.5M^2 + 2.0M + Q + 0.5)\,MV + N^3 + N^2\right]$

TABLE B - STORAGE TOTALS

STANDARD KALMAN	$0.5N^2 + 2.5N + M^2 + 2.0M + 2.0MAX(N^2, MN)$
STABILIZED KALMAN	$0.5N^2 + 2.5N + M^2 + MN + 2.0M + 2.0MAX(N^2, MN)$
SEQUENTIAL BATCH	$2.0N^2 + 5.0N + 0.5M^2 + 1.5M + MN + MVL + MAX(N^2 MN)$
POTTER SQUARE ROOT	$N^2 + N + 0.5M^2 + 0.5M + 2.0MAX(N^2,MN) + 2.0MAX(N,M)$
ANDREWS SQUARE ROOT	$N^2 + N + 1.5M^2 + 2.5M + MN + MAX(N^2,MN) + MAX(N^2,M^2) + MAX(N, M)$

TABLE C - ADDITIONAL OPERATIONS REQUIRED TO HANDLE STATE NOISE AND NON STATIONARY MEASUREMENT NOISE

	NON-STATIONARY MEASUREMENT NOISE	STATE NOISE
STANDARD KALMAN	NONE	NONE
STABILIZED KALMAN	NONE	NONE
POTTER SQUARE ROOT	$(M^3/3 + M^2 - M/3 + MQ)VL$	$(0.5N^3 + 1.5N^2 + NQ)L$
ANDREWS SQUARE ROOT	$(M^3/3 + M^2 - M/3 + MQ)VL$	$(0.5N^3 + 1.5N^2 + NQ)L$
SEQUENTIAL BATCH	$(0.5M^3 + 1.5M^2 + MQ)VL$	IMPRACTICAL*

* Within data batches

Implementation Methods Considered

Several methods of use for the sequential batch and recursive estimators were considered. Basically these variations were associated with the amount of data that are incorporated into state vector updates and the number of states updated during each filter cycle.

For the sequential batch estimator there were three methods considered. These were:

- one state vector update in 24 hours utilizing a data batch containing 24 hours of data
- two state vector updates in 24 hours utilizing a 12 hour data batch and
- minimum subset updating whereby each station pass (a data batch) is used to update only those states which are observable in that particular pass.

For the recursive estimators again three basic methods of use were considered. These were:

- full state vector updating with each observation
- full state vector updating with each observation vector and
- minimum subset updating whereby each observation is used to update only those states which are observable in that particular observation.

Table D summarizes the implementation methods which were considered in addition to listing the L, M, V and N values associated with each method. This is provided for the distributed processing concept, the simultaneous multisatellite processing concept, and for all three phases.

Results and Conclusions

The results obtained for the storage and operation totals with the various methods of implementation considered above are contained in TABLES G through V. Pictorial summaries are provided in figures 1 through 6. The results of these data are also summarized in TABLES E through G where the algorithms (segmental batch or recursive process) are listed in order of lowest requirement. This was done on the basis of the number of operations required over 24 hours, the number of operations required per system update (i.e. to update every element in the system state vector at least once), and storage (equations and data only).

Note that the sequential batch algorithm consistently ranks first in the fewest number of computations received over 24 hours with the stabilized Kalman always requiring the most. When the number of operations per system update are used for the ranking criteria, the order is reversed with the recursive estimators (the standard Kalman in particular) appearing first except is the case of clock **calibration** exploiting minimum subset updating. Here the sequential batch estimator, with one pass equal to a data batch, is slightly better. Also, the recursive estimators require the least amount of storage.

An attempt was also made to produce an overview matrix for the entire list of alternatives and to assign scores to each alternative for each category of comparison. This overview matrix is presented in TABLE Y. For each alternative concept, a score from 1 to 5 was assigned indicating whether that particular alternative had a high computational requirement (if so it was assigned a low number), had a high cost associated with its development (again a low number was assigned), or had a low technical risk (if so a high number was assigned), etc. For simplicity, equal weigh was given to all categories and the scores were summed to produce an overall score for each approach.

In general, during the scoring process, those alternatives which are non-corrector processes were scored very low in most categories primarily due to their requirements for larger computing facilities (because of their need to numerically integrate vehicle trajectories) and their high development and maintenance costs.

The overall results of this effort reflect what probably should have been intuitive namely that the simultaneous multisatellite non-corrector sequential batch process should yield the best overall accuracy but at the cost of significant initial and recurring investments. The distributed batch corrector concept on the other hand, although somewhat degraded in overall accuracy, should require a much smaller initial investment, contain a great deal of legacy in the sense that the algorithm would not have to increase in size and complexity as the GPS matures, and would probably be more serviceable in the event that experience indicates deficiencies in the original design.

TABLE D

Concept		Filter Technique	Method of Implementation	Phase I				Phase II				Phase III			
				L	M	V	N	L	M	V	N	L	M	V	N
Distributed Process	Orbit Det.	Sequential Batch Least Squares	24 hour data batch, one update every 24 hours (each vehicle)	4	1	128	7	9	1	128	7	24	1	160	7
			12 hour data batch, two updates every 24 hours (each vehicle)	8	1	64	7	18	1	64	7	48	1	80	7
			Data batch equals one pass, update with each station pass	32	1	16	7	72	1	16	7	240	1	16	7
		Recursive	State vector update at each observation*	512	1	1	7	1152	1	1	7	3840	1	1	7
	Clock, Calib.	Sequential Batch Least Squares	24 hour data batch, one update every 24 hours	1	1	512	14	1	1	1152	24	1	1	3840	56
			12 hour data batch, two updates every 24 hours	2	1	256	14	2	1	576	24	2	1	1920	56
			Minimum subset update with each station pass	32	1	16	4	72	1	16	4	240	1	16	4
		Recursive	Full state vector update at each observation*	512	1	1	14	1152	1	1	24	3840	1	1	56
			Full state vector update with each data vector (sample from all links)	32	16	1	14	32	36	1	24	32	120	1	56
			Minimum subset updating with each observation*	384 (128)	1	1	4 (2)	864 (288)	1	1	4 (2)	3072 (768)	1	1	4 (2)
Simultaneous Multi-Satellite Process		Sequential Batch Least Squares	24 hour data batch	1	1	512	42	1	1	1152	87	1	1	3840	224
			12 hour data batch	2	1	256	42	2	1	576	87	2	1	1920	224
			Minimum subset update with each station pass	32	1	16	11	72	1	16	11	240	1	16	11
		Recursive	Full state vector update with each observation*	512	1	1	42	1152	1	1	87	3840	1	1	224
			Full state vector update with each data vector	32	16	1	42	32	36	1	87	32	120	1	224
			Minimum subset updating with each observation*	384 (128)	1	1	11 (4)	864 (288)	1	1	11 (4)	3072 (768)	1	1	11 (4)

* Assumes one observation every 15 min when visible

L = # dynamic updates in 24 hours

M = # of observations received at one time

N = size of state vector updated

V = # of data vectors of length M between updates

TABLE E - RELATIVE RANKING OF ALTERNATIVES WHEN USED FOR DISTRIBUTED ORBIT DETERMINATION

RANK	OPERATIONS REQUIRED OVER 24 HOURS	OPERATIONS REQUIRED PER SYSTEM UPDATE	STORAGE
1	SEQ. BATCH - 24 HR BATCH	STANDARD KALMAN	STANDARD KALMAN
2	SEQ. BATCH - 12 HR BATCH	POTTER SQUARE ROOT	STABILIZED KALMAN
3	SEQ. BATCH - ONE PASS BATCH	ANDREWS SQUARE ROOT	POTTER SQUARE ROOT
4	STANDARD KALMAN	STABILIZED KALMAN	ANDREWS SQUARE ROOT
5	POTTER SQUARE ROOT	SEQ. BATCH - ONE PASS BATCH	SEQ. BATCH - ONE PASS BATCH
6	ANDREWS SQUARE ROOT	SEQ. BATCH - 12 HR BATCH	SEQ. BATCH - 12 HR BATCH
7	STABILIZED KALMAN	SEQ. BATCH - 12 HR BATCH	SEQ. BATCH - 24 HR BATCH

TABLE F - RELATIVE RANKING OF ALTERNATIVES WHEN USED FOR MULTISATELLITE CLOCK CALIBRATION

RANK	OPERATIONS REQUIRED OVER 24 HOURS	OPERATIONS REQUIRED PER SYSTEM UPDATE	STORAGE
1	SEQ. BATCH WITH MSU *	SEQ. BATCH WITH MSU	STANDARD KALMAN WITH MSU
2	STANDARD KALMAN WITH MSU	STANDARD KALMAN WITH MSU	STABILIZED KALMAN WITH MSU
3	SEQ. BATCH - 24 HR BATCH	POTTER SQUARE ROOT WITH MSU	POTTER SQUARE ROOT WITH MSU
4	SEQ. BATCH - 12 HR BATCH	ANDREWS SQUARE ROOT WITH MSU	ANDREWS SQUARE ROOT WITH MSU
5	POTTER SQUARE ROOT WITH MSU	STABILIZED KALMAN WITH MSU	SEQ. BATCH WITH MSU
6	ANDREWS SQUARE ROOT WITH MSU	SEQ. BATCH - 12 HR BATCH	SEQ. BATCH - 12 HR BATCH
7	STABILIZED KALMAN WITH MSU	SEQ. BATCH - 24 HR BATCH	SEQ. BATCH - 24 HR BATCH

*MINIMUM SUBSET UPDATING

TABLE G - RELATIVE RANKING OF ALTERNATIVES WHEN USED FOR SIMULTANEOUS MULTISATELLITE PROCESSING

RANK	OPERATIONS REQUIRED OVER 24 HOURS	OPERATIONS REQUIRED PER SYSTEM UPDATE	STORAGE
1	SEQ. BATCH WITH MSU*	STANDARD KALMAN WITH MSU	STANDARD KALMAN WITH MSU
2	SEQ. BATCH - 24 HR BATCH	POTTER SQUARE ROOT WITH MSU	STABILIZED KALMAN WITH MSU
3	SEQ. BATCH - 12 HR BATCH	ANDREWS SQUARE ROOT WITH MSU	POTTER SQUARE ROOT WITH MSU
4	STANDARD KALMAN WITH MSU	SEQ. BATCH WITH MSU	ANDREWS SQUARE ROOT WITH MSU
5	POTTER SQUARE ROOT WITH MSU	STABILIZED KALMAN WITH MSU	SEQ. BATCH WITH MSU
6	ANDREWS SQUARE ROOT WITH MSU	SEQ. BATCH - 12 HR BATCH	SEQ. BATCH - 24 HR BATCH
7	STABILIZED KALMAN WITH MSU	SEQ. BATCH - 24 HR BATCH	SEQ. BATCH - 24 HR BATCH

*MINIMUM SUBSET UPDATING

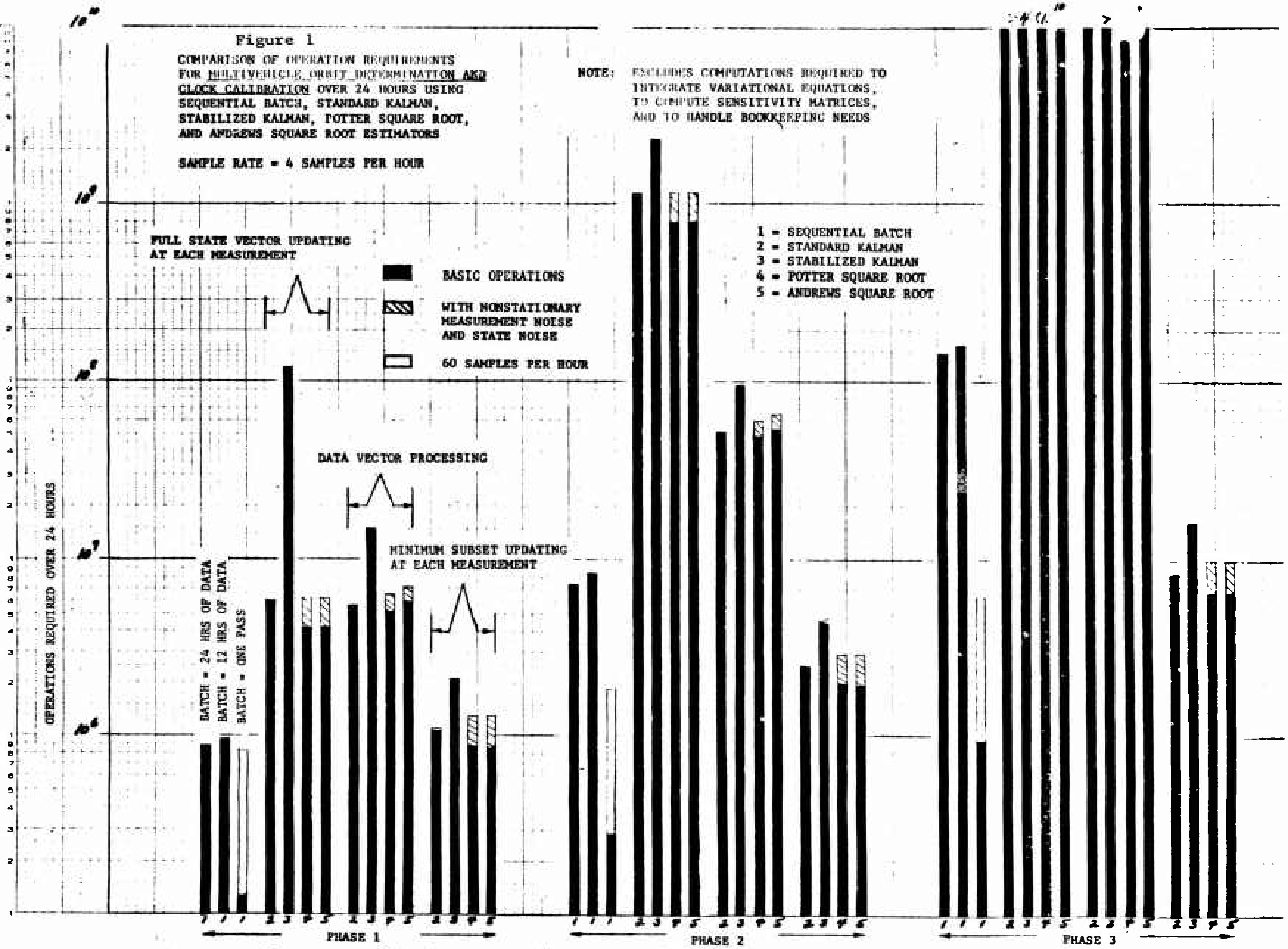


Figure 1
COMPARISON OF OPERATION REQUIREMENTS FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION OVER 24 HOURS USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS
SAMPLE RATE = 4 SAMPLES PER HOUR
NOTE: EXCLUDES COMPUTATIONS REQUIRED TO INTEGRATE VARIATIONAL EQUATIONS, TO COMPUTE SENSITIVITY MATRICES, AND TO HANDLE BOOKKEEPING NEEDS
FULL STATE VECTOR UPDATING AT EACH MEASUREMENT
BASIC OPERATIONS
WITH NONSTATIONARY MEASUREMENT NOISE AND STATE NOISE
60 SAMPLES PER HOUR
1 = SEQUENTIAL BATCH
2 = STANDARD KALMAN
3 = STABILIZED KALMAN
4 = POTTER SQUARE ROOT
5 = ANDREWS SQUARE ROOT
DATA VECTOR PROCESSING
MINIMUM SUBSET UPDATING AT EACH MEASUREMENT
OPERATIONS REQUIRED OVER 24 HOURS
BATCH = 24 HRS OF DATA
BATCH = 12 HRS OF DATA
BATCH = ONE PASS
PHASE 1
PHASE 2
PHASE 3

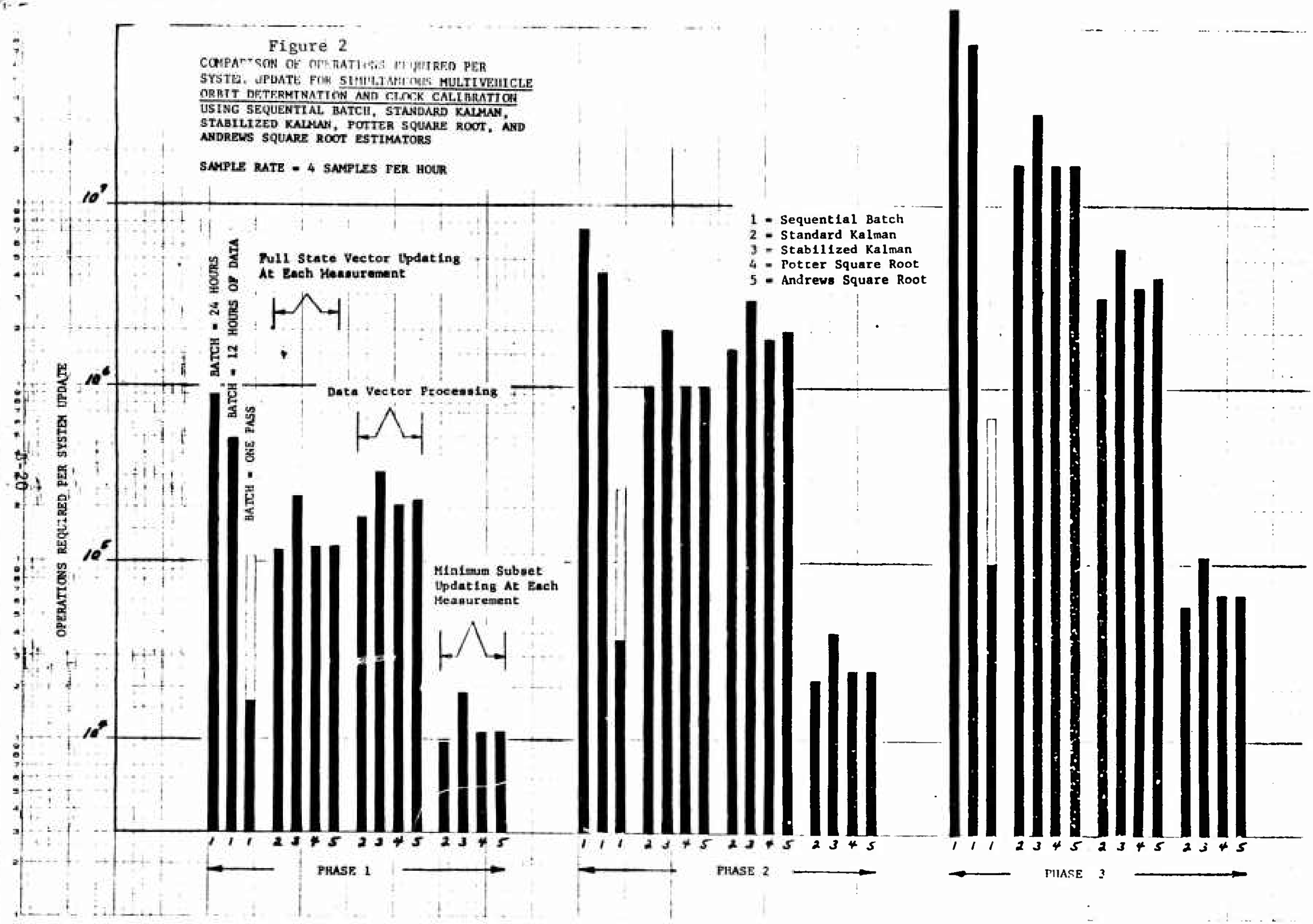


Figure 2

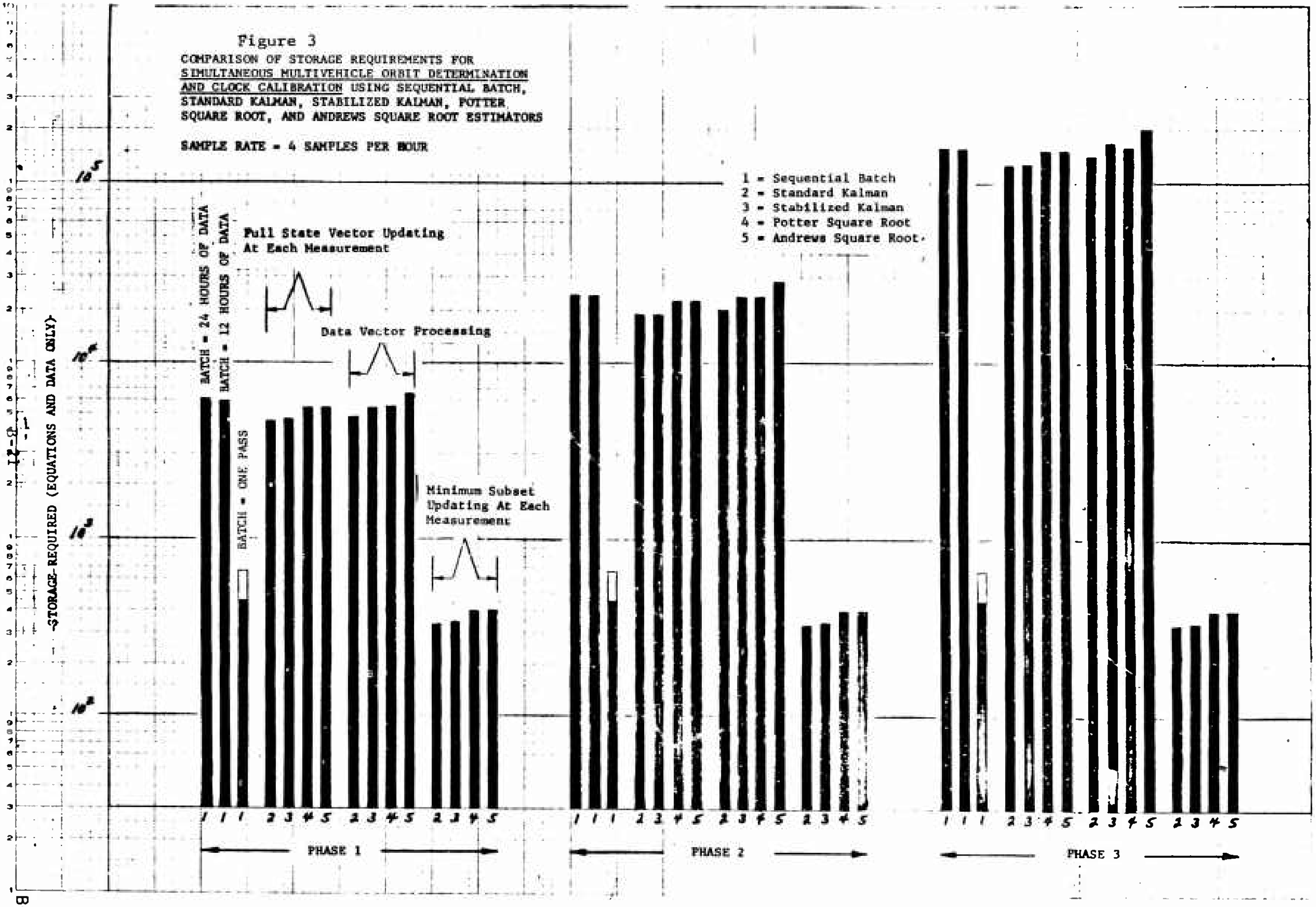
COMPARISON OF OPERATIONS REQUIRED PER SYSTEM UPDATE FOR SIMULTANEOUS MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS

SAMPLE RATE = 4 SAMPLES PER HOUR

Figure 3

COMPARISON OF STORAGE REQUIREMENTS FOR SIMULTANEOUS MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS

SAMPLE RATE = 4 SAMPLES PER HOUR



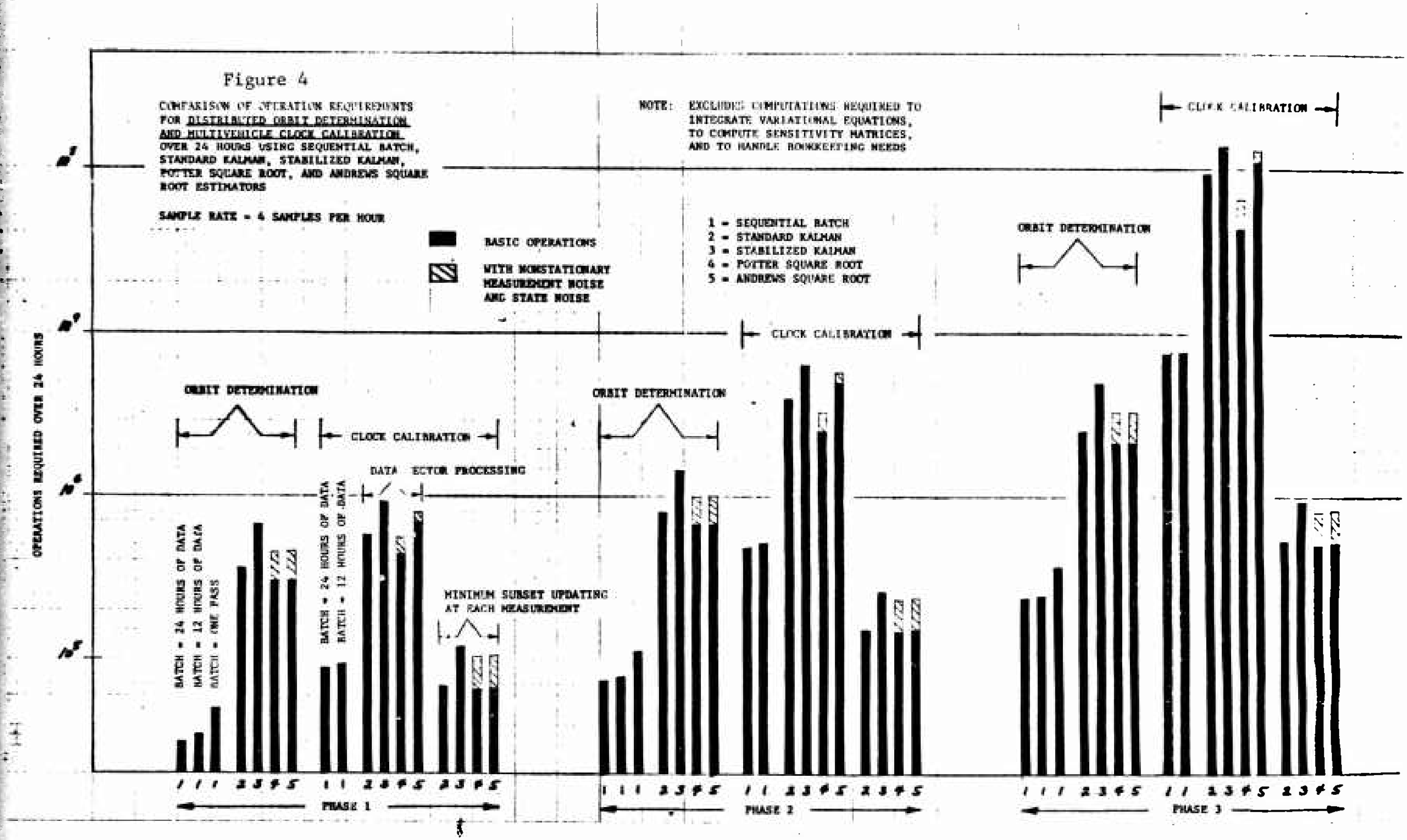


Figure 4

COMPARISON OF OPERATION REQUIREMENTS FOR DISTRIBUTED ORBIT DETERMINATION AND MULTIVEHICLE CLOCK CALIBRATION OVER 24 HOURS USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS

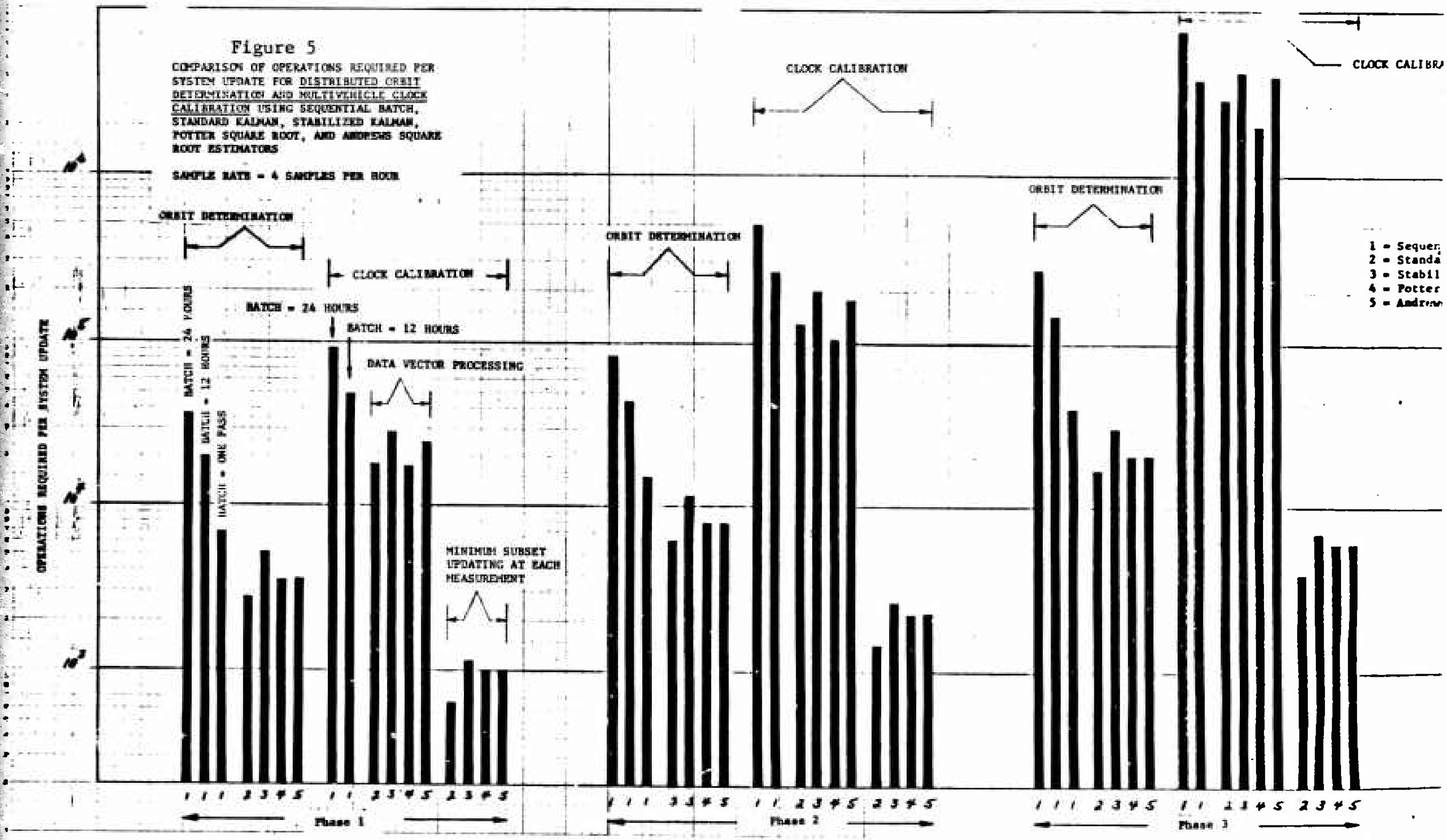


Figure 5

COMPARISON OF OPERATIONS REQUIRED PER SYSTEM UPDATE FOR DISTRIBUTED ORBIT DETERMINATION AND MULTIVEHICLE CLOCK CALIBRATION USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS

SAMPLE RATE = 4 SAMPLES PER HOUR

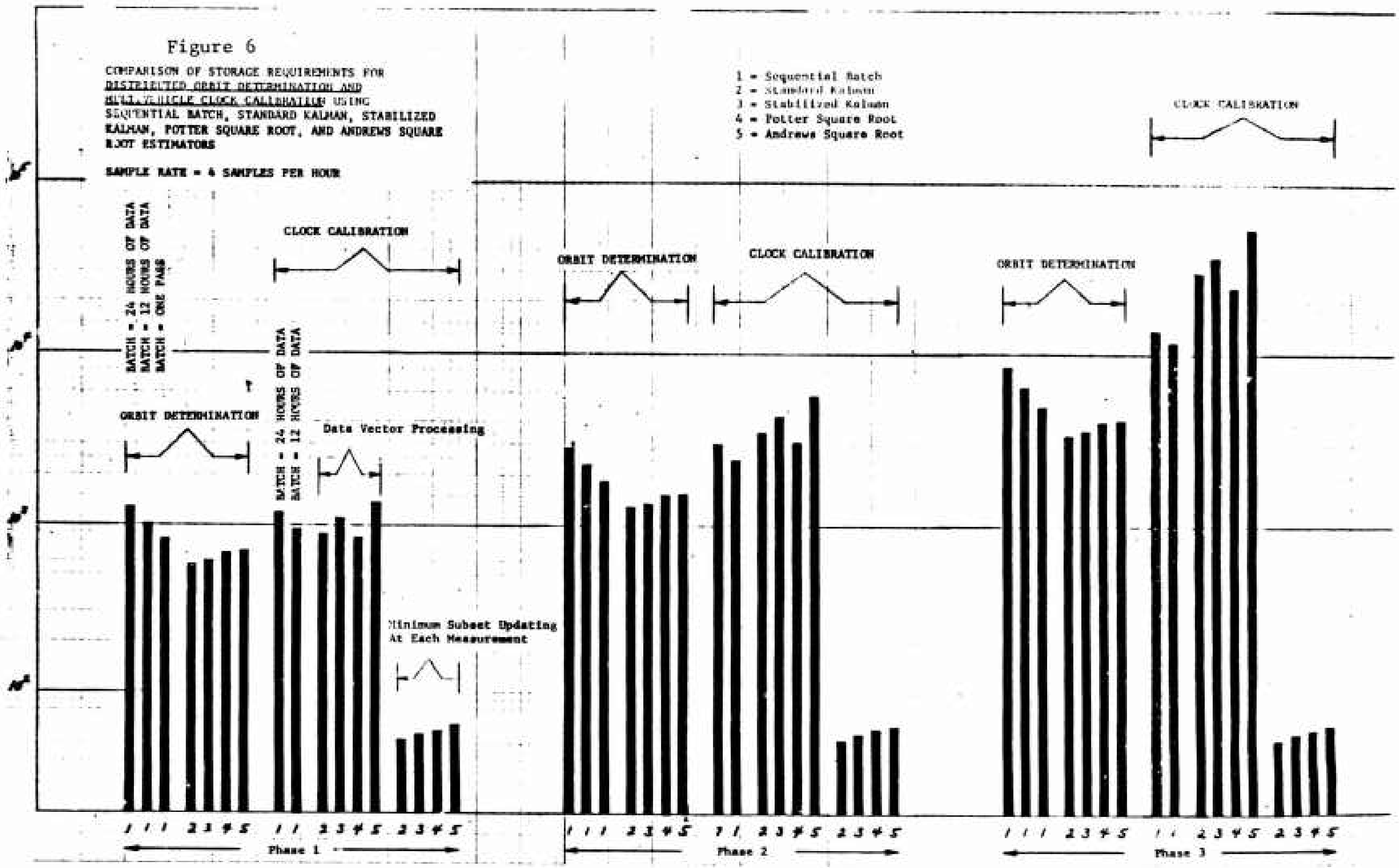


Figure 6

COMPARISON OF STORAGE REQUIREMENTS FOR DISTRIBUTED ORBIT DETERMINATION AND MULTI-VEHICLE CLOCK CALIBRATION USING SEQUENTIAL BATCH, STANDARD KALMAN, STABILIZED KALMAN, POTTER SQUARE ROOT, AND ANDREWS SQUARE ROOT ESTIMATORS

SAMPLE RATE = 4 SAMPLES PER HOUR

References: (a) I. A. Gura and A. B. Bierman, "On The Computational Efficiency of Linear Filtering Algorithms", Aerospace Report No. TC-0059(6521-01)-1, November 1970.

(b) W. M. Lear, "On The Use of Ultrastable Oscillators and a Kalman Filter to Calibrate The Earth's Gravitational Field",Ph.D. Thesis, Purdue University, 1965.

TABLE H

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR SINGLE VEHICLE ORBIT DETERMINATION OVER 24 HOURS (ONE BATCH = 24 HOURS OF DATA FOR VEHICLE 1)+

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	32,340	72,765	231,672
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	36,948	83,133	266,232
TOTAL OPERATIONS PER SYSTEM UPDATE	36,948	83,133	266,232
DATA STORAGE	512	1,152	3,840
EQUATION STORAGE	764	1,719	4,584
TOTAL STORAGE	1,276	2,871	8,424

+ Assumes One Estimator For Each Vehicle

* Within Data Batch

TABLE I

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR SINGLE VEHICLE ORBIT DETERMINATION OVER 24 HOURS (ONE BATCH = 12 HOURS OF DATA FOR VEHICLE i)+

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	34,888	78,498	246,960
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	39,496	88,866	281,520
TOTAL OPERATIONS PER SYSTEM UPDATE	19,748	44,433	140,760
DATA STORAGE	256	576	1,920
EQUATION STORAGE	764	1,719	4,584
TOTAL STORAGE	1,020	2,295	6,504

+ Assumes One Estimator For Each Vehicle

* Within Data Batch

TABLE J

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR SINGLE VEHICLE ORBIT DETERMINATION OVER 24 HOURS (ONE BATCH = ONE STATION PASS FOR VEHICLE i)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	50,176	112,896	369,264
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	54,784	123,264	403,824
TOTAL OPERATIONS PER SYSTEM UPDATE	6,848	15,408	40,382
DATA STORAGE	64	144	384
EQUATION STORAGE	764	1,719	4,584
TOTAL STORAGE	828	1,863	4,968

+ Assumes One Estimator For Each Vehicle

* Within Data Batch

TABLE K

OPERATION AND STORAGE REQUIREMENT FOR RECURSIVE ESTIMATOR WHEN USED FOR SINGLE VEHICLE ORBIT DETERMINATION OVER 24 HOURS+

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS	355,328	659,968	296,704	299,008	799,488	1,484,928	667,584	672,768	2,664,960	4,949,760	2,225,280	2,242,560
NON-STATIONARY MEASUREMENT NOISE	0	0	4,096	4,096	0	0	9,216	9,216	0	0	30,720	30,720
STATE NOISE	0	0	150,528	150,528	0	0	338,688	338,688	0	0	1,128,960	1,128,960
TOTAL OPERATIONS	355,328	659,968	451,328	453,632	799,488	1,484,928	1,015,488	1,020,672	2,664,960	4,949,760	3,384,960	3,402,240
TOTAL OPERATIONS PER UPDATE*	2,776	5,156	3,526	3,544	6,246	11,601	7,934	7,974	16,656	30,936	21,156	21,156
DATA STORAGE	4	4	4	4	9	9	9	9	24	24	24	24
EQUATION STORAGE	568	596	672	684	1,278	1,341	1,512	1,539	3,408	3,576	4,032	4,104
TOTAL STORAGE	572	600	676	688	1,287	1,350	1,521	1,548	3,432	3,600	4,056	4,128

*System Update (i.e., To Update All Vehicles)

+Assumes One Estimator For Each Vehicle

TABLE L

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION
(ONE BATCH = ALL DATA FOR ALL VEHICLES OVER 24 HOURS)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	87,808	488,208	7,498,960
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	92,416	498,576	7,533,520
TOTAL OPERATIONS PER SYSTEM UPDATE	92,416	498,576	7,533,520
DATA STORAGE	512	1,152	3,840
EQUATION STORAGE	674	1.874	9,746
TOTAL STORAGE	1,186	3,026	13,586

*Within Data Batch

TABLE M

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION (ONE BATCH = ALL DATA FOR ALL VEHICLES OVER 12 HOURS)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	92,414	510,384	7,770,224
NONSTATIONARY MEASUREMENT NOISE	4,608	10,398	35,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	97,022	520,752	7,804,784
TOTAL OPERATIONS PER SYSTEM UPDATE	48,511	260,376	3,902,392
DATA STORAGE	256	576	1,920
EQUATION STORAGE	674	1,874	9,746
TOTAL STORAGE	930	2,450	11,666

*Within Data Batch

TABLE N

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION BY UPDATING MINIMUM SUBSET OF CLOCK STATE VECTOR WITH EACH STATION PASS

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	15,904	35,424	117,408
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	20,512	45,792	151,968
TOTAL OPERATIONS PER SYSTEM UPDATE	2,564	5,724	15,197
DATA STORAGE	16	16	16
EQUATION STORAGE	74	74	74
TOTAL STORAGE	90	90	90

*Within Data Batches

TABLE O

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION OVER 24 HOURS WITH FULL CLOCK STATE VECTOR UPDATING AT EACH MEASUREMENT

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS (MILLIONS)	2.441	4.706	1.843	1.847	26.004	50.914	18.714	18.729	1,048.	2.078.	723.536	723.
NONSTATIONARY MEASUREMENT NOISE	0	0	4,096	4,096	0	0	9,216	9,216	0	0	30,720	30,720
STATE NOISE (MILLIONS)	0	0	0.903	0.903	0	0	9.151	9.151	0	0	356.751	356.751
TOTAL OPERATIONS (MILLIONS)	2.441	4.706	2.750	2.754	26.004	50.914	27.874	27.889	1,048.	2,078.	1,080.	1,080.
TOTAL OPERATIONS PER SYSTEM UPDATE	4,768	9,192	5,372	5,380	22,573	44,197	24,197	24,210	273,085	541,269	281,333	281,362
DATA STORAGE	1	1	1	1	1	1	1	1	1	1	1	1
EQUATION STORAGE	527	541	630	633	1,502	1,526	1,800	1,803	7,982	8,038	9,576	9,579
TOTAL STORAGE	528	542	631	634	1,503	1,527	1,801	1,804	7,983	8,039	9,577	9,580

TABLE P

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION BY PROCESSING DATA VECTORS CONTAINING ONE SAMPLE FROM EACH VEHICLE/STATION LINK OVER 24 HOURS

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS (MILLIONS)	0.566	0.916	0.435	0.678	4.079	6.410	2.606	4.879	94.361	140.688	43.077	109.905
NONSTATIONARY MEASUREMENT NOISE	0	0	55,296	55,296	0	0	546,816	546,816	0	0	18,918,400	18,918,400
STATE NOISE	0	0	56,448	56,448	0	0	254,208	254,208	0	0	2,972,928	2,972,928
TOTAL OPERATIONS (MILLIONS)	0.566	0.916	0.547	0.789	4.079	6.410	3.407	5.680	94.361	140.688	64.968	131.796
TOTAL OPERATIONS PER SYSTEM UPDATE	17,706	28,640	17,112	24,680	127,476	200,340	106,482	177,510	2,948,808	4,396,520	2,030,276	4,118,636
DATA STORAGE	16	16	16	16	36	36	36	36	120	120	120	120
EQUATION STORAGE	853	1,077	810	1,338	3,408	4,272	3,030	5,658	29,688	36,388	24,012	52,932
TOTAL STORAGE	869	1,093	826	1,354	3,444	4,308	3,066	5,694	29,788	36,508	24,132	53,052

TABLE Q

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE CLOCK CALIBRATION OVER 24 HOURS BY UPDATING ONLY MINIMUM SUBSET OF CLOCK SYSTEM STATE VECTOR

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS	66,944	117,120	64,896	66,304	150,624	263,520	146,016	149,184	526,848	923,136	508,416	519,168
NONSTATIONARY MEASUREMENT NOISE	0	0	4,096	4,096	0	0	9,216	9,216	0	0	30,720	30,720
STATE NOISE	0	0	35,328	35,328	0	0	79,488	79,488	0	0	276,480	276,480
TOTAL OPERATIONS	66,944	112,120	104,320	105,728	150,624	263,520	234,720	237,888	526,848	923,136	815,616	826,368
TOTAL OPERATIONS PER SYSTEM UPDATE	652	1,148	988	1,000	1,467	2,583	2,223	2,250	3,912	6,888	5,928	6,000
DATA STORAGE	1	1	1	1	1	1	1	1	1	1	1	1
EQUATION STORAGE	52	56	60	63	52	56	60	63	52	56	60	63
TOTAL STORAGE	53	57	61	64	53	57	61	64	53	57	61	64

TABLE R

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR SIMULTANEOUS MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION (ONE BATCH = ALL DATA FOR ALL VEHICLES OVER 24 HOURS

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	836,136	7,398,741	144,660,544
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	840,744	7,409,109	144,695,104
TOTAL OPERATIONS PER SYSTEM UPDATE	840,744	7,409,109	144,695,104
DATA STORAGE	512	1,152	3,840
EQUATION STORAGE	5,546	23,231	151,874
TOTAL STORAGE	6,058	24,383	155,714

*Within Data Batch

TABLE S

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR SIMULTANEOUS MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION (ONE BATCH = ALL DATA FOR ALL VEHICLES OVER 12 HOURS)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	951,678	8,405,418	161,645,120
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	956,286	8,415,786	161,679,680
TOTAL OPERATIONS PER SYSTEM UPDATE	478,143	4,207,893	80,839,840
DATA STORAGE	256	576	1,920
EQUATION STORAGE	5,546	23,231	151,874
TOTAL STORAGE	5,802	23,807	153,794

*Within Data Batch

TABLE T

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION OVER 24 HOURS BY UPDATING MINIMUM SUBSET OF SYSTEM STATE VECTOR WITH EACH STATION PASS (F=4 SAMPLES/HOUR)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	128,282	283,602	935,946
NONSTATIONARY MEASUREMENT NOISE	4,608	10,368	34,560
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	132,890	293,970	970,506
TOTAL OPERATIONS PER SYSTEM UPDATE	16,612	36,747	97,056
DATA STORAGE	16	16	16
EQUATION STORAGE	431	431	431
TOTAL STORAGE	447	447	447

*Within Data Batch

TABLE U

OPERATION AND STORAGE REQUIREMENTS FOR SEQUENTIAL BATCH ESTIMATOR WHEN USED FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION OVER 24 HOURS BY UPDATING MINIMUM SUBSET OF SYSTEM STATE VECTOR WITH EACH STATION PASS (F=60 SAMPLES PER HOUR)

ITEM	PHASE I	PHASE II	PHASE III
BASIC OPERATIONS	837,914	1,880,274	6,258,186
NONSTATIONARY MEASUREMENT NOISE	69,120	155,520	518,400
STATE NOISE	IMPRACTICAL*	IMPRACTICAL*	IMPRACTICAL*
TOTAL OPERATIONS	907,034	2,035,794	6,776,586
TOTAL OPERATIONS PER SYSTEM UPDATE	105,380	254,475	669,664
DATA STORAGE	240	240	240
EQUATION STORAGE	431	431	431
TOTAL STORAGE	671	671	671

*Within A Data Batch

TABLE V

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION OVER 24 HOURS (FULL STATE VECTOR UPDATE AT EACH MEASUREMENT)

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS (MILLIONS)	59.706	117.982	41.647	41.658	1,164.503	2,315.576	793.934	793.986	7,000	10,000	40,000	40,000
NONSTATIONARY MEASUREMENT NOISE	0	0	4096	4096	0	0	9216	9216	0	0	30,720	30,720
STATE NOISE (MILLIONS)	0	0	20.471	20.471	0	0	393.078	393.078	0	0	22,000	22,000
TOTAL OPERATIONS (MILLIONS)	59.706	117.982	62.123	62.134	1,164.	2,315.	1,187.	1,187.	70,000	100,000	70,000	70,000
TOTAL OPERATIONS PER SYSTEM UPDATE (MILLIONS)	0.116	0.230	0.121	0.121	1.010	2.010	1.030	1.030	17	34	17	17
DATA STORAGE	1	1	1	1	1	1	1	1	1	1	1	1
EQUATION STORAGE	4517	4559	5418	5421	19,142	19,229	22,968	22,971	126,002	126,226	151,200	151,200
TOTAL STORAGE	4518	4560	5419	5422	19,143	19,230	22,969	22,972	126,003	126,227	151,201	151,201

TABLE W

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION BY PROCESSING DATA VECTORS CONTAINING ONE SAMPLE FROM EACH VEHICLE/STATION LINK

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT
BASIC OPERATIONS (MILLIONS)	5.657	10.489	5.241	5.813	51.580	95.637	47.954	54.073	1,016	1,852.	943	1,125.
NONSTATIONARY MEASUREMENT NOISE	0	0	55,296	55,296	0	0	546,816	546,816	0	0	18,918,400	18,918,400
STATE NOISE (MILLIONS)	0	0	1.279	1.279	[illegible]	0	10.918	10.918	0	0	182.	182.
TOTAL OPERATIONS (MILLIONS)	5.657	10.489	6.576	7.148	51.580	95.637	59.419	65.539	1,016	1,852.	1,144.	1,326.
TOTAL OPERATIONS PER SYSTEM UPDATE (MILLIONS)	0.176	0.327	0.205	0.223	1,611.	2,988.	1,856.	2,048.	31,771.	37,902.	35,769.	41,466.
DATA STORAGE	16	16	16	16	36	36	36	36	120	120	120	120
EQUATION STORAGE	4,787	5,459	5,538	6,456	20,472	23,604	23,598	28,011	140,520	167,400	158,340	199,636
TOTAL STORAGE	4,803	5,475	5,554	6,472	20,508	23,604	23,634	28,047	140,340	167,520	158,460	199,756

TABLE X

OPERATION AND STORAGE REQUIREMENTS FOR RECURSIVE ESTIMATORS WHEN USED FOR MULTIVEHICLE ORBIT DETERMINATION AND CLOCK CALIBRATION OVER 24 HOURS BY UPDATING ONLY MINIMUM SUBSET OF SYSTEM STATE VECTOR AT EACH MEASUREMENT

ITEM	PHASE I				PHASE II				PHASE III			
	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.	STANDARD KALMAN	STAB. KALMAN	POTTER SQ. RT.	ANDREWS SQ. RT.
BASIC OPERATIONS	1,101,824	2,099,072	860,5[illegible]	863,744	2,479,104	4,722,912	1,936,224	1,943,424	8,461,824	16,126,464	6,602,112	6,626,304
NONSTATIONARY MEASUREMENT NOISE	0	0	4,096	4,096	0	0	9,216	9,216	0	0	30,720	30,720
STATE NOISE	0	0	425,088	425,088	0	0	956,448	956,448	0	0	3,260,160	3,260,160
TOTAL OPERATIONS	1,101,829	2,099,072	1,289,728	1,292,928	2,479,104	4,722,912	2,901,888	2,909,088	8,461,864	16,126,464	9,892,992	9,917,184
TOTAL OPERATIONS PER SYSTEM UPDATE	9,640	18,396	11,222	11,248	21,690	41,391	25,250	25,308	57,840	110,376	67,332	67,488
DATA STORAGE	1	1	1	1	1	1	1	1	1	1	1	1
EQUATION STORAGE	33[illegible]	343	396	399	332	343	396	399	332	343	396	399
TOTAL STORAGE	333	344	397	400	333	344	397	400	333	344	397	400

TABLE Y - TRADE STUDY OVERVIEW MATRIX

CHARACTERISTIC \ ALTERNATIVE			DISTRIBUTED PROCESSING CONCEPT — ORBIT DETERMINATION				DISTRIBUTED PROCESSING CONCEPT — CLOCK CALIBRATION		SIMULTANEOUS MULTIVEHICLE OD AND CLOCK CALIBRATION			
			MUSTANG (RECURSIVE)	CELESTE CORRECTOR	TRACE SEQ. BATCH	AOES	SEQUENTIAL BATCH	RECURSIVE FILTER	SEQ. BATCH CORRECTOR	RECURSIVE CORRECTOR	TRACE SEQ. BATCH	
COMPUTATIONAL REQUIREMENTS		DATA STORAGE	3	3	3	3	2	5	2	5	1	1 = HIGH REQUIREMENTS
		PROGRAM STORAGE	5	5	3	3	4	5	2	2	1	5 = LOW REQUIREMENTS
		# INST. REQ.	5	5	2	2	5	1	3	1	2	
		WORD SIZE	5	5	1	1	5	5	5	5	1	
ACCURACY		STABILITY	4	4	4	4	5	3	4	3	5	1 = LOW ACCURACY
		UERE	4	4	4	3	3	5	5	5	5	5 = HIGH ACCURACY
	HARDWARE	COMPUTER	5	5	2	2	5	5	3	3	1	
		COMM. LINES	5	5	4	4	—	—	5	4	5	1 = HIGH COST
		LEASE TIME	5	5	2	2	—	—	5	5	1	5 = LOW COST
	SOFTWARE	DEVELOPMENT	5	3	3	2	5	4	2	2	1	
		MAINTENANCE	5	4	3	3	5	4	2	2	1	
TECHNICAL RISK		PROBEN CAPABILITY	3	5	4	1	5	3	3	2	5	1 = HIGH RISK
		EASE OF MODIFICATION	5	4	2	2	4	5	3	3	1	5 = LOW RISK
LEGACY			5	5	4	2	5	5	5	5	1	1 = POOR LEGACY
TOTALS			64	62	41	34	53	50	49	47	31	5 = GOOD LEGACY

*USER EQUIVALENT RANGE ERROR

REPORT C9

EPHEMERIS AND CLOCK
PROCESSING SIMULATIONS

REPORT C-9

EPHEMERIS AND CLOCK SIMULATIONS

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REPORT C9, PART II

EPHEMERIS AND CLOCK PROCESSING SIMULATIONS

1.0 INTRODUCTION

In this report four aspects of the ephemeris and clock processing are discussed.

In Section 2 the results of simulations of the effects of ephemeris and clock-state errors on the user navigation error are presented and discussed. A preliminary discussion of the scope of the simulation effort, the sources of error considered and the measures of performance used is followed by a summary of the numerical results which is followed by brief statements of conclusions drawn from those results.

Section 3 contains detailed descriptions of the conditions constituting the baselines under which the investigations of this report were conducted. The orbits, perturbation sources, tracking data and network, parameters of the solution vector, user considerations, and differences between the current and the earlier (January 30, 1974) baseline are described. A table summarizing the concepts and conditions is included.

The investigations into representing the ephemeris to the user are discussed in detail in Section 4. The methods and errors are presented and it is concluded that the users will be provided with sets of sixth-degree polynomials; each individual polynomial representing a component of the state vector and each set of polynomials representing a satellite ephemeris over a period of 1 hour with sufficient sets available to represent the ephemeris of all satellites for 5 days.

The uncertainty in a users ability to determine his present location relative to a previous estimate of location is the subject of Section 5. This relative error is defined, investigated, and evaluated for the WSMR user.

1.1 Scope of Simulations

The simulation effort covers three sets of cases. The bulk of the early simulation effort was concentrated in the multi-satellite processing approach in which all the satellite orbit elements and all clock state parameters are solved for simultaneously. This approach was directly simulated by the covariance analysis mode of the TRACE orbit determination program. However, as the computer processing requirements of the later phases of the GPS project became appreciated, a second approach was investigated -- the distributed processing approach in which the orbital elements of each satellite are solved for independently using time differences in range data, and then using the range data itself in a separate calculation of clock state parameters. This distributed processing approach has been employed in two versions, referred to as (1) the January 30 baseline in which the Vandenberg site is used for a reference timing source and (2) the current baseline with the reference timing source taken at the northernmost tracking site with the greatest span of satellite visibility. Simulation results for these three cases are presented separately.

The design goal has been stated to be a user positioning accuracy, or UERE, of twelve feet at two hours after all vehicles have been loaded which was assumed to be three hours after the end of the 48-hour tracking span. Although bounds necessary for satisfactory system performance have not been specified on the magnitudes of the foregoing errors, realistic conditions have been chosen to approach the design goal. The degree to which this has been achieved is indicated in the results that follow.

Figure 9-1 depicts the simulations.

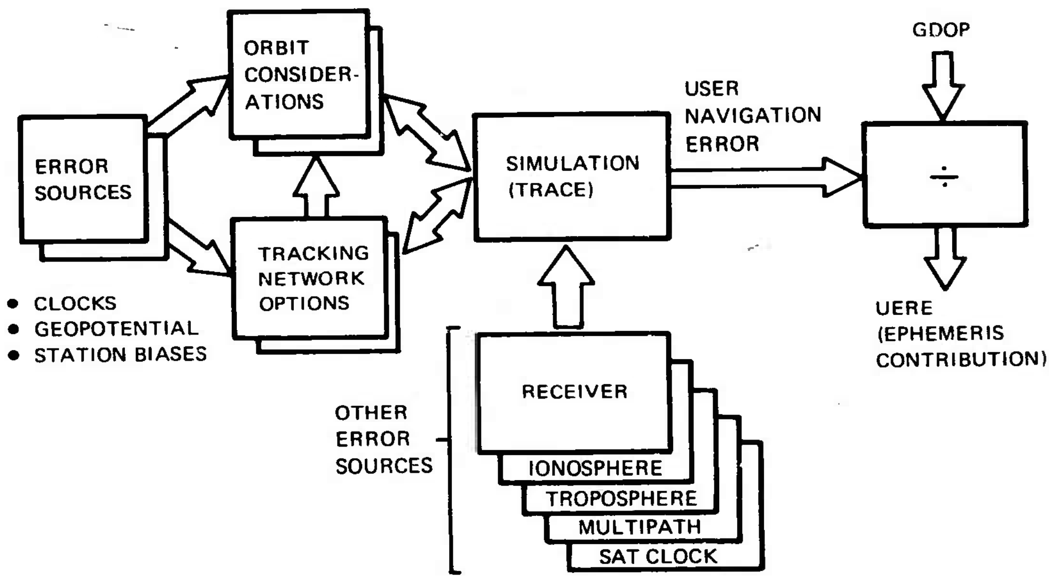

Figure 9-1 Simulation

1.2 Sources of Error

Three sources of error are considered in the simulation results which follow:

a. Noise in the observational data

b. Tracking station location uncertainties

c. Errors in the orbital model

The noise in the observational data includes tropospheric and ionospheric model error effects in addition to receiver noise and effects of quantizing the data when it is reported. Tracking station locations are parameters of the overall orbit determination problem that cannot be solved for on a pass-by-pass basis. Following an initial calibration a residual uncertainty will exist in these parameters. These uncertainties are simulated in the TRACE runs through the use of Q parameters. Likewise, residual errors will exist in the orbital model, principally due to limited knowledge of the geopotential. An assessment of these effects is also treated through the use of the Q parameter capability of TRACE.

1.3 Measures of Performance

While the ultimate test of system performance is acknowledged to be the size of the User Equivalent Range Error (UERE), some of the results of the simulation effort have been expressed in terms of other parameter errors in an effort to provide additional information as to how certain effects operate on the total error picture. The three sets of parameters that are additionally used are the following:

a. Satellite position error components to show ephemeris error effects

b. Clock state parameters (offset and drift) to indicate the behavior of timing errors

c. User navigation error components (latitude, etc.) in order to assess individual contributions to the UERE.

2.0 PRESENTATION OF RESULTS

The conditions for all of the simulation results presented here are defined in detail in Section 3 below. The salient features of the error analysis baselines are these:

a. 48 hour observation span

b. 15-minutes between observations

c. Range data equivalent noise = 5 feet standard deviation

d. Range difference data noise equivalent to range rate standard deviation of 0.005 ft/sec.

e. Tracking station location errors assumed to be 10 feet spherical.

f. Geopotential uncertainties equivalent to 3% error in $J_{2,2}$ and 5% error in $J_{3,2}$.

g. Solution state vector comprised of six orbital elements plus solar radiation parameter and satellite clock state parameters for offset and drift.

2.1 Multi-Satellite Processing Results for January 30 Baseline

Satellite and user position errors are presented for the multi-satellite processing approach in three sets of tables, each set corresponding to certain assumptions with regard to the source of error. In each case data are presented for five points in the orbit corresponding to user observations at six hour intervals (ie, when the satellite configuration is the same for symmetrically placed users).

2.1.1 Influence of Measurement Noise Alone

In Table 9-1 are presented the RSS satellite position errors for each of the four satellites along with the components and RSS total of the user positioning

TABLE 9-1

SATELLITE AND USER POSITION ERRORS (in ft)

FOR MULTI-SATELLITE PROCESSING WITH MEASUREMENT NOISE ALONE

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	7.6	9.1	9.2	10.6	11.0
RSS SAT 2	7.9	8.6	9.6	10.0	11.5
RSS SAT 3	7.7	12.0	9.4	15.0	11.4
RSS SAT 4	8.1	11.5	10.1	14.5	12.2
USER LATITUDE	2.0	2.7	2.5	3.4	3.1
USER LONGITUDE	1.5	2.3	1.9	2.9	2.3
USER ALTITUDE	5.3	7.6	6.6	9.7	8.0
USER R BIAS	3.5	5.0	4.4	6.4	5.3
RSS - USER	6.8	9.8	8.5	12.5	10.3
UERE	1.6	2.3	2.0	2.9	2.4

Δt = HOURS FROM END OF TRACKING SPAN

error and the corresponding User Equivalent Range Error (UERE) for the five observation times. These values reflect only the errors in range observations, and assume that 11 other parameters of the problem are error-free. This, of course, is a very optimistic result, useful mainly for comparison between processing approaches and as a point of departure for assessment of the extent to which other sources of error enter the picture.

2.1.2 Added Effects of Station Location Errors

The total effect of errors in observations due to noise plus the effect of uncertain tracking station locations is shown in the data of Table 9-2, which presents satellite and user position errors in the same format as before. The differences between the entries in this and the previous table are due to station location errors and are seen to be significant. As this is a more realistic treatment of the errors, additional detail on the components of the satellite position error is presented in the data of Table 9-3. The greatest errors are seen to arise from the in-track component. The cross-track effects are unchanging in time. Both of these characteristics are consistent with the dynamics of the orbit and the type of observations used.

2.1.3 Added Effect of Geopotential Uncertainties

The composite effect of observation noise, station location errors and uncertainties in the geopotential model on orbital and user position errors is presented in the error data of Table 9-4. Although the total error is higher in this case than when the geopotential uncertainty is neglected, the effect is mainly in satellite position and is not as strongly felt in the user positioning accuracy, particularly for short prediction intervals.

2.1.4 Clock State Errors With and Without Geopotential Uncertainties

To further assess the importance of the uncertainty of the geopotential model, data are presented in Table 9-5 comparing the uncertainties in the clock states

TABLE 9-2

SATELLITE AND USER POSITION ERRORS (in ft)

FOR MULTI-SATELLITE PROCESSING WITH MEASUREMENT
NOISE AND STATION LOCATION ERRORS

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 24
RSS SAT 1	29.1	40.0	29.5	40.2	30.5
RSS SAT 2	34.4.	38.2	38.1	39.9	42.5
RSS SAT 3	37.8	43.1	39.5	45.1	41.7
RSS SAT 4	39.9	44.1	41.0	45.7	42.4
USER LATITUDE	7.2	8.7	7.9	9.9	8.8
USER LONGITUDE	6.3	11.1	6.9	11.3	7.7
USER ALTITUDE	13.3	15.6	14.6	17.3	16.1
USER R BIAS	7.9	10.8	8.9	12.0	10.2
RSS - USER	18.2	23.6	20.1	25.9	22.4
UERE	4.3	5.6	4.7	6.1	5.3

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-3

SATELLITE POSITION ERROR COMPONENTS (in ft)

FOR MULTI-SATELLITE PROCESSING WITH
MEASUREMENT NOISE AND STATION LOCATION ERRORS

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RADIAL					
SAT 1	5.4	5.6	5.8	6.1	6.3
SAT 2	6.1	6.1	6.5	6.4	6.9
SAT 3	5.0	5.1	5.0	5.1	5.0
SAT 4	5.6	5.4	5.6	5.4	5.7
IN-TRACK					
SAT 1	17.7	32.3	18.2	32.8	19.6
SAT 2	26.3	31.1	30.9	33.1	36.1
SAT 3	20.2	28.9	23.4	31.9	26.8
SAT 4	24.2	30.7	26.0	32.9	28.2
CROSS-TRACK					
SAT 1	22.5	22.5	22.5	22.5	22.5
SAT 2	21.3	21.3	21.3	21.3	21.3
SAT 3	31.5	31.5	31.5	31.5	31.5
SAT 4	31.2	31.2	31.2	31.2	31.2

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-4

SATELLITE AND USER POSITION ERRORS (in ft)

FOR MULTI-SATELLITE PROCESSING WITH MEASUREMENT NOISE, STATION LOCATION ERRORS AND GEOPOTENTIAL UNCERTAINTIES

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	37	86	45	110	55
RSS SAT 2	43	68	53	87	65
RSS SAT 3	40	52	45	60	53
RSS SAT 4	47	47	54	52	63
USER LATITUDE	6.9	11.3	7.2	11.8	8.3
USER LONGITUDE	10.2	17.9	12.6	23.8	15.4
USER ALTITUDE	15.5	19.2	18.4	23.6	22.1
USER R BIAS	9.7	12.7	11.9	15.6	14.6
RSS - USER	21.9	31.3	26.3	38.8	31.7
UERE	5.2	7.4	6.2	9.1	7.5

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-5

CLOCK STATE ERRORS WITH MULTI-SATELLITE PROCESSING

CLOCK	WITHOUT GEOPOTENTIAL ERROR		WITH GEOPOTENTIAL ERROR	
	OFFSET (FT)	RATE (FT/SEC)	OFFSET (FT)	RATE (FT/SEC)
SATELLITE 1	7.1	1.9×10^{-5}	8.1	2.4×10^{-5}
SATELLITE 2	8.1	2.5×10^{-5}	8.9	3.1×10^{-5}
SATELLITE 3	7.0	1.8×10^{-5}	7.9	3.2×10^{-5}
SATELLITE 4	7.1	1.7×10^{-5}	8.1	3.2×10^{-5}
NORTHEAST STATION	9.6	2.1×10^{-5}	9.8	2.4×10^{-5}
PACIFIC STATION	10.1	2.9×10^{-5}	10.2	3.2×10^{-5}
NORTHWEST STATION	10.1	2.6×10^{-5}	10.2	2.7×10^{-5}

(offset and rate) of the four satellites and three monitor stations with an without the effect of geopotential uncertainties. It should be emphasized at this point that the clock error being simulated here is that due to inability to fit the clock data and not that due to inability to predict clock variation. Investigations of the latter error source are discussed in the report on that subject. It will be noted that there is only a small effect on the offsets and the monitor station clock errors are insensitive to the geopotential uncertainty. However, the satellite clock rates are somewhat affected by this source of error, a fact which is consistent with the degraded user positioning accuracy for large prediction intervals as observed above.

2.2 Distributed Processing (January 30 Baseline)

Satellite and user position error data for the distributed processing approach of the January 30 baseline are presented in two sets of tables similar in format to the first three tables of the preceding subsection, for comparison with the multi-satellite processing concept. The influence of geopotential uncertainties has been ignored in this approach because of the relatively minor role it played in the results of the multi-satellite approach. Comparisons of UERE and system error growth rates are also presented.

2.2.1 Influence of Measurement Noise Alone

Table 9-6 presents satellite and user position error results considering measurement noise to be the only source of error. As with the data of Table 9-1, these results are unrealistically optimistic.

2.2.2 Added Effect of Station Location Errors

The results change as indicated in Table 9-7 when the effects of station location errors are included. As with multi-satellite processing, a significant increase is observed. The details of the satellite position error are presented in Table 9-8 and show some interesting effects when compared to similar data for the multi-satellite approach presented earlier in Table 9-3. The radial components are not significantly different but the cross-track error shows an increase; in fact, this is the dominant component for two of the satellites.

TABLE 9-6

SATELLITE AND USER POSITION ERRORS (in ft)

FOR DISTRIBUTED PROCESSING WITH MEASUREMENT NOISE ALONE

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	24.4	31.8	26.3	33.1	28.6
RSS SAT 2	25.1	23.4	29.3	26.0	34.0
RSS SAT 3	22.3	25.6	24.7	28.9	27.6
RSS SAT 4	19.2	24.7	21.7	28.1	24.6
USER LATITUDE	3.8	6.2	4.8	7.2	5.8
USER LONGITUDE	3.1	6.0	4.0	7.0	4.9
USER ALTITUDE	10.8	19.0	13.6	22.3	16.6
USER R BIAS	7.0	12.6	8.9	14.8	10.9
RSS - USER	13.8	24.4	17.4	28.6	21.3
UERE	3.2	5.7	4.1	6.7	5.0

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-7

SATELLITE AND USER POSITION ERRORS (in ft)

FOR DISTRIBUTED PROCESSING WITH MEASUREMENT NOISE AND STATION LOCATION ERRORS

PARAMETER	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	55.1	66.0	55.9	66.7	57.1
RSS SAT 2	37.5	45.3	40.9	46.6	44.9
RSS SAT 3	49.7	55.3	51.3	57.7	53.3
RSS SAT 4	39.4	42.9	40.5	44.1	41.9
USER LATITUDE	7.7	14.9	8.0	15.5	8.5
USER LONGITUDE	5.2	9.1	6.0	9.9	6.8
USER ALTITUDE	14.8	42.0	17.3	43.9	19.9
USER R BIAS	7.3	27.6	9.3	28.9	11.3
RSS - USER	18.9	53.2	22.0	55.7	25.3
UERE	4.5	12.5	5.2	13.1	6.0

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-8

SATELLITE POSITION ERROR COMPONENTS (in ft)
FOR DISTRIBUTED PROCESSING WITH MEASUREMENT
NOISE AND STATION LOCATION ERRORS

PARAMETER	$\Delta t = 3$	$\Delta t = 9$	$\Delta t - 15$	$\Delta t = 21$	$\Delta t = 27$
RADIAL					
SAT 1	5.6	5.8	6.2	6.4	6.9
SAT 2	7.7	7.9	8.0	8.1	8.2
SAT 3	9.0	9.5	8.9	9.4	8.9
SAT 4	6.4	6.5	6.5	6.6	6.7
IN-TRACK					
SAT 1	23.4	43.2	25.3	44.2	27.6
SAT 2	31.5	40.9	35.4	41.9	40.0
SAT 3	13.6	27.5	18.5	32.1	23.6
SAT 4	29.1	33.7	30.5	35.2	32.4
CROSS-TRACK					
SAT 1	49.5	49.5	49.5	49.5	49.5
SAT 2	18.8	18.8	18.8	18.3	18.8
SAT 3	47.0	47.0	47.0	47.0	47.0
SAT 4	25.8	25.8	25.8	25.8	25.8

Δt = HOURS FROM END OF TRACKING SPAN

2.2.3 Comparison of User Errors

The differences in the two processing approaches in terms of their effect on user error are highlighted in the bar charts of Figures 9-2 and 9-3. Figure 9-2 shows the time history of UERE sampled at the five observation times for both processing approaches considering only measurement noise (without station errors). Although the percentage differences between the results of the two concepts are large, both concepts produce errors well within the design goal. Figure 9-3 shows the effect of introducing station location errors. In addition to differences between the two processing concepts, one sees a magnified difference between the users. For the northern hemisphere users (Δt = 3, 15, 27) there was a small increase in error and the two concepts produced similar results. For the southern hemisphere users, the results of both concepts approximately doubled, so that the large percentage differences between the concepts still exists.

A further comparison of the two processing approaches is afforded by the data presented in Table 9-9, which shows the growth rates for satellite position and satellite clock offset errors, and for the UERE at the initial observation opportunity over the WSMR test area.

COMPARISON OF USER EQUIVALENT RANGE ERRORS
(WITHOUT STATION LOCATION ERRORS)

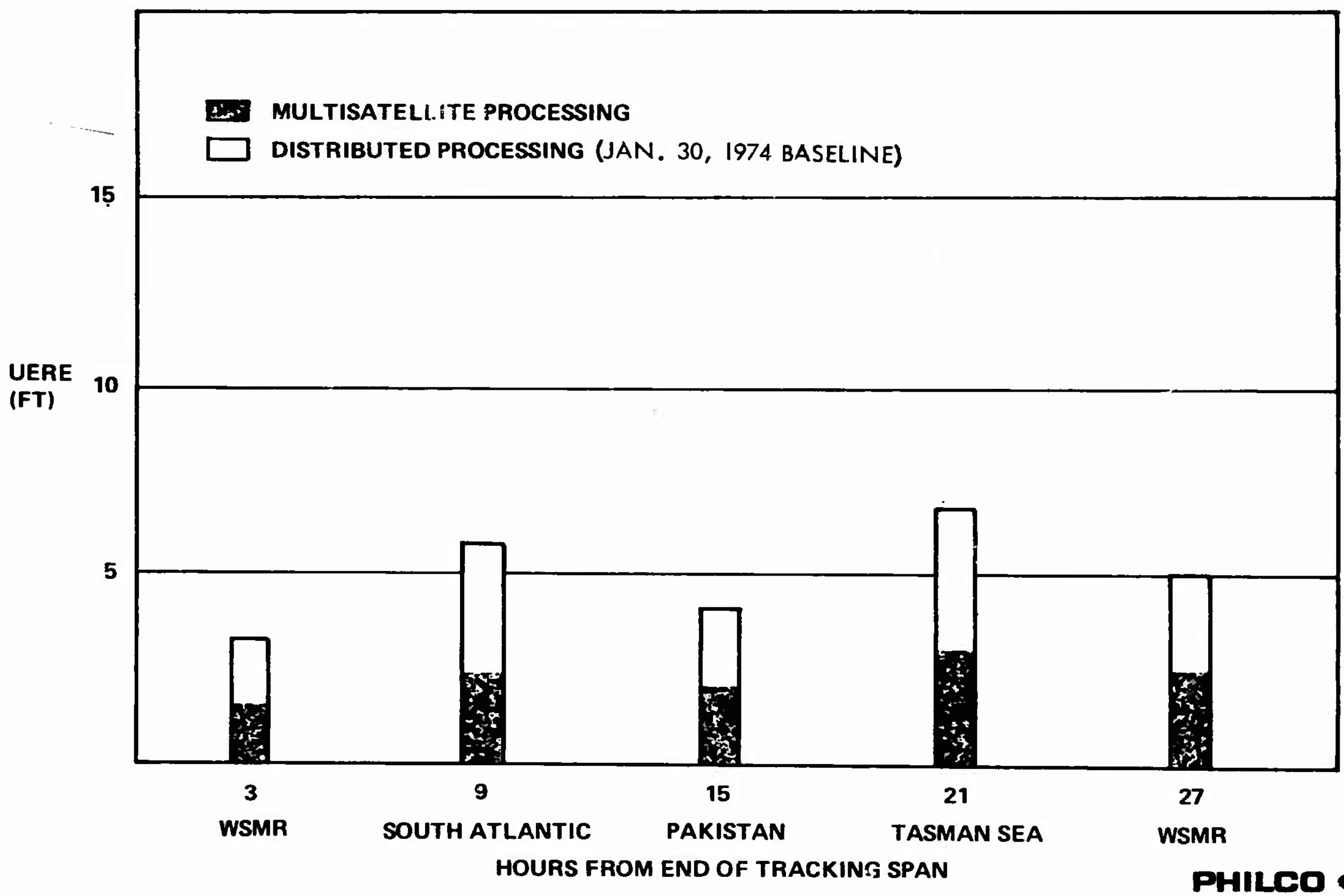

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Figure 9-2

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COMPARISON OF USER EQUIVALENT RANGE ERRORS
(WITH STATION LOCATION ERRORS)

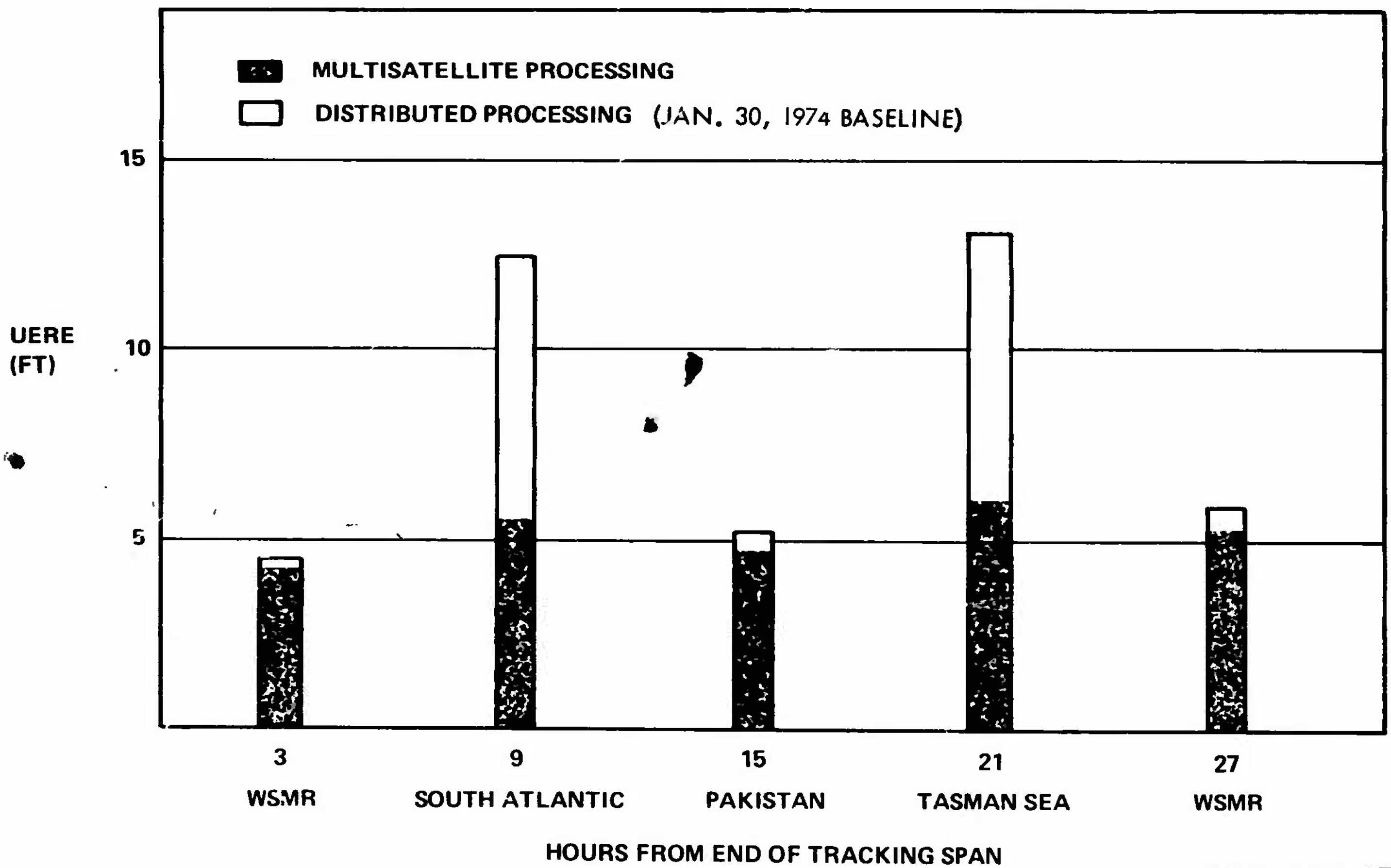

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Figure 9-3

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TABLE 9-9

SYSTEM ERROR GROWTH RATES* (IN FT/DAY)

PARAMETER	VEHICLE	MULTISATELLITE	DISTRIBUTED
RSS POSITION ERRORS	1	1.4	2.0
	2	8.1	7.4
	3	3.9	3.6
	4	2.5	2.5
VEHICLE CLOCK OFFSETS	1	1.6	1.3
	2	2.2	1.6
	3	1.6	1.3
	4	1.5	1.5
WSMR	-	1.0	1.5

*48 HOURS OF DATA, FOR MEASUREMENT NOISE AND STATION LOCATION ERROR EFFECTS

2.3 Distributed Processing Current Baseline

A change from the JAN 30 Baseline was made in the distributed processing approach in that the reference timing station (that station for which range observations are processed) was taken to be the Northwest tracking site rather than at the Vandenberg location. The Northwest station has the greatest satellite visibility and this change, as expected, produced better navigation performance over a broader geographic area.

2.3.1 Satellite and User Position Errors

Table 9-10 presents a tabulation of satellite and user position errors for the current baseline which include only the effects of measurement noise. Table 9-11 presents similar data which also include the effects of station location errors. For this latter case the components of satellite position error are listed in Table 9-12. These three tables reflect results obtained under the same conditions as those of the two preceding sections so that the effects of the different approaches may be compared. A graphical comparison of UERE between the current baseline for distributed processing and the multi-satellite processing approach is given in Figure 9-4.

It is noted that the character of the time variation of the errors has changed. The oscillation in UERE error has shifted phase so that greater accuracy is achieved in the southern hemisphere and less in the northern hemisphere, although the differences between the two are not as large. This phase reversal is not found in the satellite position errors. Upon closer examination of the elements of the user position error in Table 9-11, it is found that this apparently anomalous effect is due to the behavior of the altitude (and to a lesser extent, the range bias) error. The same behavior is observed (below) in other simulations with the current baseline, so that it is not to be dismissed as an error in program execution. Since this reversal in phase is not noted when station location errors are ignored (see Table 9-10) the effect is attributed to the way station location errors are propagated, possibly causing a correlation among the orbit position errors.

TABLE 9-10

SATELLITE AND USER POSITION ERRORS (in ft)
FOR DISTRIBUTED PROCESSING, CURRENT BASELINE,
WITH MEASUREMENT NOISE ONLY

PARAMETERS	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	22.9	27.2	25.0	28.9	27.5
RSS SAT 2	19.9	21.9	22.4	24.3	25.4
RSS SAT 3	27.4	35.3	29.5	39.2	32.0
RSS SAT 4	21.7	27.9	24.4	32.2	27.7
USER LATITUDE	5.0	6.8	5.7	7.9	6.6
USER LONGITUDE	4.2	6.3	4.8	7.2	5.5
USER ALTITUDE	16.0	18.9	17.7	22.7	19.6
USER R BIAS	10.1	12.0	11.3	14.4	12.6
RSS - USER	20.0	24.3	22.2	29.0	24.8
UERE	4.7	5.7	5.2	6.8	5.8

Δt = HOURS FROM END OF TRACKING SPAN

TABLE 9-11

SATELLITE AND USER POSITION ERRORS (in ft)
FOR DISTRIBUTED PROCESSING, CURRENT BASELINE
WITH MEASUREMENT NOISE AND STATION LOCATION ERRORS

PARAMETERS	Δt = 3	Δt = 9	Δt = 15	Δt = 21	Δt = 27
RSS SAT 1	52.3	67.7	53.5	69.6	55.1
RSS SAT 2	55.8	55.7	58.8	56.9	62.1
RSS SAT 3	53.1	78.1	55.7	83.3	59.1
RSS SAT 4	38.4	42.9	39.9	46.3	42.0
USER LATITUDE	7.5	15.4	8.1	16.0	8.8
USER LONGITUDE	8.5	12.7	8.9	14.0	9.4
USER ALTITUDE	31.9	24.5	31.1	27.1	30.7
USER R BIAS	19.3	14.1	18.9	16.4	18.8
RSS - USER	39.0	34.6	38.3	38.2	38.2
UERE	9.2	8.1	9.0	9.0	9.0

TABLE 9-12

SATELLITE POSITION ERROR COMPONENTS (in ft)
FOR DISTRIBUTED PROCESSING, CURRENT BASELINE
WITH MEASUREMENT NOISE AND STATION LOCATION ERRORS

PARAMETER	$\Delta t = 3$	$\Delta t = 9$	$\Delta t = 15$	$\Delta t = 21$	$\Delta t = 27$
RADIAL					
SAT 1	7.4	7.3	8.0	8.0	8.7
SAT 2	13.3	13.4	14.0	14.1	14.7
SAT 3	5.9	6.0	5.9	6.0	5.9
SAT 4	5.5	5.2	5.8	5.4	6.2
IN-TRACK					
SAT 1	21.6	48.0	24.2	50.6	27.3
SAT 2	38.3	38.1	42.3	39.6	46.6
SAT 3	24.9	62.5	30.2	68.9	35.9
SAT 4	24.6	31.3	26.8	35.7	29.8
CROSS-TRACK					
SAT 1	47.1	47.1	47.1	47.1	47.1
SAT 2	38.3	38.3	38.3	38.3	38.3
SAT 3	46.5	46.5	46.5	46.5	46.5
SAT 4	28.9	28.9	28.9	28.9	28.9

Δt = HOURS FROM END OF TRACKING SPAN

USER EQUIVALENT RANGE ERRORS

(WITH STATION LOCATION ERRORS)

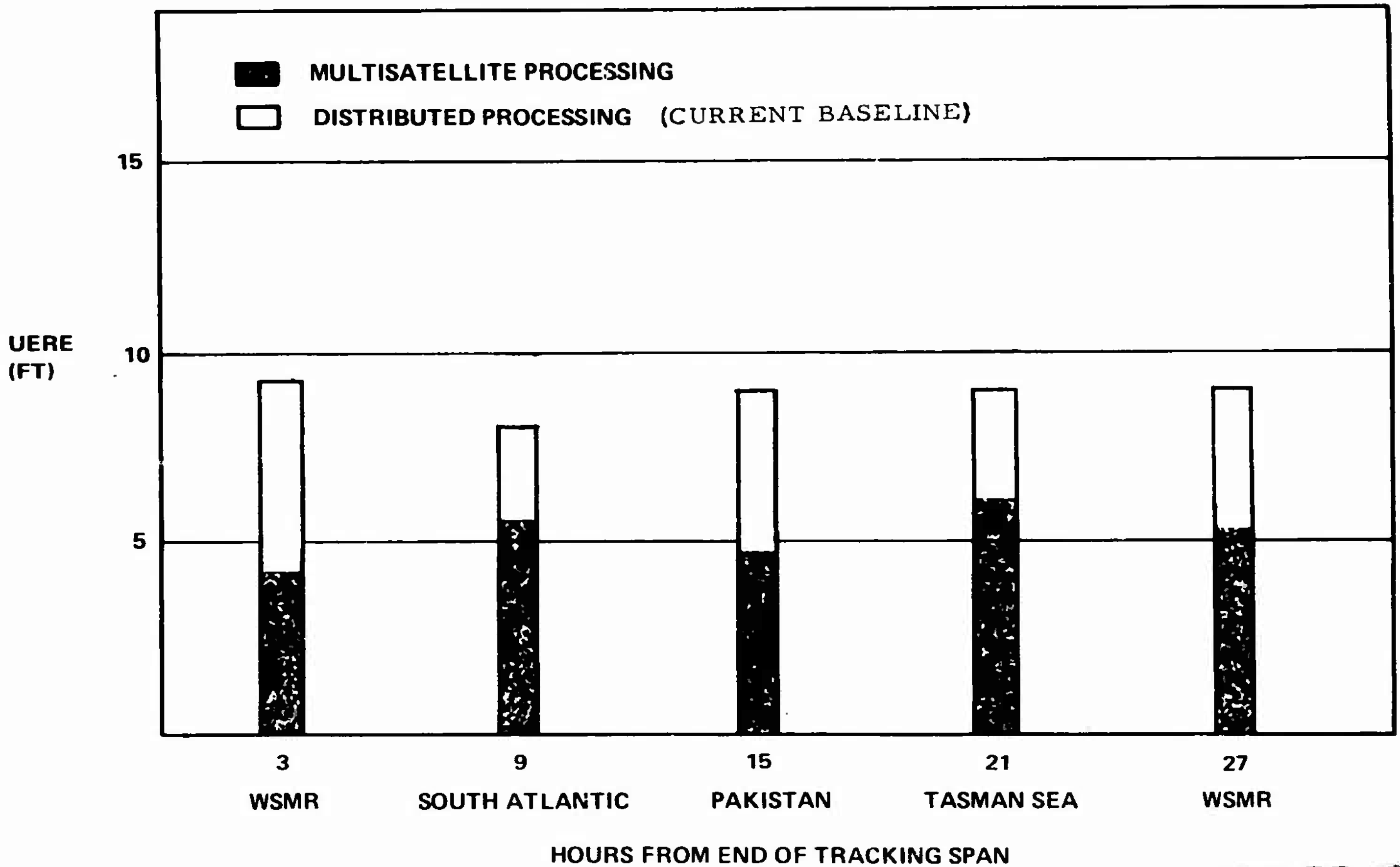

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Figure 9-4

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2.3.2 Effect of Station Clock Frequency Error

A simulation was performed to assess the effect of an error in station clock frequency. This was accomplished by considering an equivalent bias error in range rate observations of 0.001 ft/sec. The user position error results, presented in Table 9-13, shows very little difference from the comparable data of Table 9-11 where this error was not present.

2.3.3 Effects of Tracking Network Reduction

A question on the amount of degradation user positioning accuracy that would occur if the Northeast tracking station were to be eliminated was answered in the results shown in Table 9-14. It is noted that the northern hemisphere observations are more strongly affected in this case.

2.3.4 Effects of Replacing a Tracking Station

The effect of providing a broader base for tracking coverage was investigated by replacing the Northeast tracking station with one at Guam, in the western Pacific. The improvement on the results for this case (shown in Table 9-15) is principally associated with southern hemisphere users. As noted earlier, the reversal of phase of UERE variation in time is evident again in this case, principally in the altitude component of user position errors.

TABLE 9-13

USER ONE-SIGMA POSITIONING ERRORS (IN. FT.)

WITH DISTRIBUTED PROCESSING

INCLUDING STATION CLOCK FREQUENCY ERROR

	Δt=3	Δt=9	Δt=15	Δt=21	Δt=27
LATITUDE	7.8	15.6	8.4	16.2	9.1
LONGITUDE	8.6	12.8	9.0	14.0	9.4
ALTITUDE	32.1	24.9	31.3	27.5	30.9
R BIAS	19.5	14.3	19.1	16.7	19.0
RSS	39.3	35.1	38.7	38.7	38.5
UERE	9.3	8.3	9.1	9.1	9.1

TABLE 9-14

USER ONE-SIGMA POSITIONING ERRORS (IN FT.)

WITH BOS OBSERVATIONS EXCLUDED

	Δt=3	Δt=9	Δt=15	Δt=21	Δt=27
LATITUDE	8.6	19.5	9.2	19.9	9.9
LONGITUDE	11.8	11.3	12.1	12.3	12.4
ALTITUDE	37.5	24.2	37.2	27.3	37.0
R BIAS	24.3	15.1	24.2	17.6	24.2
RSS	47.1	36.4	46.8	40.0	47.0
UERE	11.1	8.6	11.0	9.4	11.1

TABLE 9 -15

USER ONE-SIGMA POSITIONING ERRORS (IN FT.)

WITH DISTRIBUTED PROCESSING

AND GUAM REPLACING BOS

	Δt=3	Δt=9	Δt=15	Δt=21	Δt=27
LATITUDE	8.0	13.2	8.6	13.9	9.3
LONGITUDE	8.8	10.2	9.2	11.3	9.7
ALTITUDE	31.6	24.1	30.8	26.6	30.5
R BIAS	19.9	13.7	19.6	16.0	19.5
RSS	39.2	32.4	38.6	35.8	38.6
UERE	9.2	7.6	9.1	8.4	9.1

CONDITIONS

USERS — TIME FROM END OF TRACKING (HRS)		CURRENT BASELINE (KOD RANGING)							1/30/74 BASELINE (VTS RANGING)		
		① BASELINE DISTRIBUTED PROCESSING	② FREQUENCY OFFSET σ = 0.001'/SEC	③ GUAM REPLACES BOS	④ BOS EXCLUDED	⑤ REFERENCE LONGITUDE AT VTS	⑥ STATION LOCATION σ's = 0	⑦ RANGE RATE NOISE = 0.05'/SEC	⑧ DISTRIBUTED PROCESSING	⑨ SIMULTANEOUS MULTI-SATELLITE PROCESSING	⑩ GEOPOTENTIAL σ's INCLUDED
3	WSMR	9.2	9.3	9.2	11.1	10.0	4.7	13.6	4.5	4.3	5.2
9	SOUTH ATLANTIC	8.1	8.3	7.6	8.6	9.0	5.7	12.3	12.5	5.6	7.4
15	PAKISTAN	9.0	9.1	9.1	11.0	9.9	5.2	13.8	5.2	4.7	6.2
21	TASMAN SEA	9.0	9.1	8.4	9.4	9.7	6.7	13.1	13.1	6.1	9.1
27	WSMR	9.0	9.1	9.1	11.1	9.8	5.8	14.0	6.0	5.3	7.5

Figure 9-5 User Equivalent Range Error (in feet) For Baseline and Variations

2.4 Concluding Remarks

In reviewing the results described in this presentation of the simulation effort, the following observations are made:

1) Considering only the effect of measurement noise yields a very optimistic picture of user positioning accuracy.

2) Tracking station location errors of 10 feet spherical standard deviation have a significant effect on user navigation performance.

3) The inclusion of the effects of geopotential uncertainties have a small additional degrading effect.

4) The distributed processing approach does not provide the full accuracy of the multi-satellite approach, but the difference is not so large as to be unacceptable.

5) The current baseline distributed processing approach provides more uniform (than JAN 30 baseline) user error behavior over time, yielding better performance for southern hemisphere users.

6) The effect of station clock frequency error on range difference observations appears insignificant.

7) Removal of the Northeast tracking station from the network increase UERE for northern hemisphere users.

8) Replacing the Northeast tracker with one at Guam improves the navigation performance of southern hemisphere users.

3.0 Assumed Conditions

The TRACE program executed in its covariance analysis mode was used to simulate the conditions described below. **Figure 9-6 presents a summary.**

3.1 Orbit Description

The epoch time 0000 hours, 9/21/73 was arbitrarily chosen because of its convenience and was used throughout the simulations. The epoch conditions of the reference orbits are expressed in terms of classical elements as follows:

two orbit planes with two vehicles in each

semi-major axis	87,145,102 feet
eccentricity	0.0001
inclination	63°
right ascension of ascending node	195° (vehicles 1 and 2) 75° (vehicles 3 and 4)
argument of perigee	0°
mean anomalies	41°, 81°, 64°, and 124° (vehicles 1, 2, 3, and 4, respectively)

The above values of right ascension and mean anomaly were selected to optimize the duration of simultaneous visibility and GDOP.

3.2 Orbit Perturbations

Forces acting on the satellite in addition to the earth's gravity central force field are considered to include zonal gravity harmonics J_2 through J_6 and tesseral gravity harmonics from $J_{2,1}$ through $J_{5,5}$. Lunar and solar gravitation effects were modeled along with the Sun's radiation pressure effect (through CPAW = 10^{-9}). No drag or other in-track accelerations were considered.

3.3 Tracking Data and Network

Tracking data from four stations was simulated; a master station in Southern California and three monitor stations located in Hawaii, the Pacific Northwest and New England. The following representative station locations were used:

SUMMARY OF CONCEPTS AND CONDITIONS

	SIMULTANEOUS MULTISATELLITE CONCEPT	DISTRIBUTED PROCESSING CONCEPT (CALIBRATE SATELLITE CLOCKS)
TRACKING DATA		
RANGE	15 MIN/48 HOURS	15 MIN/48 HOURS – "MASTER" MONITOR
RANGE DIFFERENCE	NONE	15 MIN/48 HOURS – OTHER MONITORS
RANGE SIGMA	5 FT	5 FT
RANGE DIFFERENCE SIGMA		.005 FT/SEC
SOLUTION (P) PARAMETERS		
ORBIT STATES	7/SATELLITE	7/SATELLITE
CLOCK STATES	2/CLOCK	2/CLOCK
CONSIDER (Q) PARAMETERS		
SENSOR LOCATIONS	10 FT SPHERICAL	10 FT SPHERICAL
USER SOLUTIONS		
PREDICTION TIMES	3, 9, 15, 21, 27 HOURS	3, 9, 15, 21, 27 HOURS
LOCATIONS	WSMR, SOUTH ATLANTIC, PAKISTAN, TASMAN SEA, WSMR	WSMR, SOUTH ATLANTIC, PAKISTAN, TASMAN SEA, WSMR
(P) PARAMETERS	LOCATION AND TIME	LOCATION AND TIME
DATA	RANGES (4)	RANGES (4)

Figure 9-6

STATION	LATITUDE	LONGITUDE
VTS	32.83	239.50
HUL	21.56	201.76
KOD	57.60	207.82
BOS	42.95	288.37

Tracking station location errors were assumed to be 10-feet spherical. The table below gives the equivalent standard deviations for each station. (Note that the longitude errors are corrected for latitude).

STATION	LONGITUDE (deg)		LATITUDE (deg)	ALTITUDE (ft)
	Simultaneous multi-sat	Distributed		
VTS	0	3.34×10^{-5}	2.74×10^{-5}	10
HUL	2.95×10^{-5}	2.95×10^{-5}	2.74×10^{-5}	10
KOD	5.12×10^{-5}	0	2.74×10^{-5}	10
BOS	3.74×10^{-5}	3.74×10^{-5}	2.74×10^{-5}	10

In the simultaneous processing concept, the meridian of the VTS station is considered the reference while that of KOD is the reference in the distributed processing concept. In the simulations, the appropriate longitude uncertainty was set to zero.

In the simulations of the distributed concept, the KOD station observation type was range and the BOS, HUL, and VTS observation types were range rate with noise standard deviations of 5 ft. and 0.005 ft/sec, respectively. This value of range rate standard deviation is based on the assumption that ground clocks will be atomic. See Report C-9, Part II for the effect of crystal clocks (standard deviation = .05 feet/second).

These observations were obtained at 15-minute intervals over a 48-hour span whose start and stop times were selected from considerations of processing and uplink loading of the satellites before the visibility period over the WSMR test site.

3.4 Solution State Vector

The parameters solved for include the orbit elements of each satellite and the offset and drift of the satellite clocks. The following tabulation identifies the TRACE variables and the initial uncertainty attributed to each:

Parameter	A Prior Uncertainty
Orbit elements (equinoctial)	
AF, AG	1×10^{-5} radians
N	1×10^{-8} deg/sec
L	1×10^{-3} degrees
CHI, PSI	1×10^{-5} radians
CPAW	15% of CPAW
Satellite Clocks	
Offset (VSB)	100 feet.
Drift (VSBD)	6×10^{-4} fps

3.5 User Considerations

In simulating the user positioning determination with TRACE, the following guidelines were observed:

1. User located at Holloman test site (Latitude 33N, Longitude 254E).
2. User observations considered error-free.
3. User observations were taken 3 hours after the observation span.
4. To show error growth in time, alternate user observations were taken 6 hours later (Lat. -33, Long. 334), 12 hours later (Lat. 33, Long. 74), and so on for twenty-four hours.
5. Users located as in 4 above view the same satellite geometry and, therefore, have the same GDOP. The value was computed to be 4.25 and was used in determining the UERE's presented in this report.

3.6 Jan 30, 1974 Baseline

Early simulations were based on the conditions described at the GPS Working Group meeting, Jan. 30, 1974. This earlier baseline was different for the distributed processing concept in that the VTS station was the ranging station and its meridian was considered the reference. Then the VTS longitude uncertainty was set to zero and that of KOD was set to 5.12×10^{-5} degrees.

4.0 EPHEMERIS REPRESENTATION ERROR

4.1 Introduction and Conclusions

In previous sections we have discussed orbit determination and ephemeris prediction as sources of error in user positioning. This section addresses the problem of representing the predicted ephemerides to the user and presents the results of investigations of the two most promising methods of representation.

The investigations into representing the ephemeris to the user lead to the conclusion that the users will be provided with a set of three sixth order polynomials to be updated each hour. Such a representation with a 513 bit data frame length will result in less than a 1 foot contribution to UERE.

4.2 Requirements and Selection Criteria

The requirements of the ephemeris representation are to provide the user with a short downlink message so that he may begin computation as soon as pssible, to minimize the computation required to determine satellite position, and to permit satellite positioning sufficiently accurate to meet his own positioning accuracy requirements. The first two factors are important because they contribute significantly to time-to-fix and most significantly to time-to-first-fix.

The following criteria reflect these requirements and form the basis for selection of the recommended method of ephemeris representation:

a. accuracy of representation
b. navigation data frame length
c. computational load placed on the user
d. satellite storage requirements

The accuracy of the representation is primarily dependent on two factors. First is the fit error due to the inability of the representation to exactly represent the ephemeris. Second is truncation error introduced by seeking to minimize the length of the data frame.

The major portion of the downlink message is dedicated to ephemeris representation. Message size is the prime factor in determining the delay a user will encounter between the time he turns on his receiver and the time he may make his first position fix. For this reason, navigation data frame length is a prime factor in the selection of a mode of representation.

The first step in each navigation solution is an updated satellite position fix. In order to minimize the computational load to the user, the number of operations required for each such fix should be minimized.

In the event that the upload station is unable to update the ephemeris data stored in any satellite, each satellite is required to store ephemeris data sufficient to support user navigation for five days. The representation method must provide the required accuracy subject to the limited memory size and absence of satellite computation capability.

4.3 Parameters of the Investigation

Investigations into the ephemeris representation were conducted with emphasis on two considerations: method of representation and duration of representation. Three methods of representation were considered. They are orbit elements, Fourier series, and polynomials. The first two methods were eliminated from consideration early in the investigation due to the computational load imposed upon the user by their requirements to evaluate numerous trigonometric functions. The Fourier series requires the evaluation of a sequence of such functions while orbit elements require coordinate rotations dependent on trigonometric function evaluation. It was concluded early, then, that the ephemerides should be represented to the user by polynomials.

That choice of methods requires new considerations: the method of forming the polynomials and the coordinate system in which the ephemerides will be represented. Computational efficiency was the primary factor in selecting earth-fixed, cartesian coordinates. Since that is the system in which the user computation will be made, satellite ephemerides in an earth-centered inertial coordinate system would require transformation. It was determined that the ECI system would require at least 100 more operations per satellite fix than would an earth-fixed representation.

4.4 Comparison of Polynomial Options

Two techniques for ephemeris representation by polynomials were considered: least squares polynomial filter and interpolation.

There are two essential ideas underlying the polynomial filter approach.

1. We are not required to model the actual physical process; if the polynomial is of adequate degree it will automatically seek out the information of interest and give a reasonable estimate of it.

2. By using least squares, we are not forcing the polynomial to equal any of the observations exactly. This results in a certain amount of smoothing.

The basic rationale for interpolation is as follows.

1. We are not required to model the actual process; if the order of the interpolating polynomial is sufficient. If the data includes only negligible noise, and if the sampling interval is sufficiently small, then the interpolation will give a reasonable estimate.

2. By interpolating, we are forcing the polynomial to go through several points, combinations of which are taken to estimate interior points.

The two approaches were compared by investigation their performance with respect to two 80 minute sample intervals within an orbit. An earth fixed X coordinate system was assumed. The interpolation technique used was Gregory-Newton, which uses successive differences $\Delta^i y$. The position is expressed as

$$X(t) = \sum_{i=0}^{N} \frac{\Delta^i x_o}{i!} \prod_{j=0}^{N} (k-j)$$

where $K = {}^{t/}\Delta t$ and the $\Delta^i X_o$ are the coefficients transmitted. The polynomials fit by a least squares technique express position as

$$X(t) = \sum_{i=0}^{N} a_i t^i$$

The results are shown in Table 9-16.

On the basis of this comparison, which shows the least squares approach better in each category, the subsequent investigation centered exclusively on the polynomial curve fitting approach.

TABLE 9-16

Performance Comparison of Interpolation Against Curve Fitting for Two Sample 80 Minute Intervals

Data Type	Polynomial Degree	Representation Type	Mean Residual Error (ft)	Data Length (Bits)	Calculations *	Calculations +
"Good" 80 Minute Interval	5th Deg	INT	.48	139	10	9
		LSQ	.26	124	5	5
	6th Deg	INT	.37	152	12	11
		LSQ	.25	138	6	6
"Bad" 80 Minute Interval	5th Deg	INT	9.6	142	10	9
		LSQ	6.9	137	5	5
	6th Deg	INT	.05	156	12	11
		LSQ	.04	148	6	6

4.5 Fit Error

The degree of polynomial required to fit a given set of data must be determined empirically. A given order polynomial fitting identical sets of data from different parts of an orbit will yield different errors in the fit. As is illustrated in Figure 9-7, the RSS error of fitting all three components remains rather constant throughout an orbit. However, the error in a particular dimension may change by more than an order of magnitude.

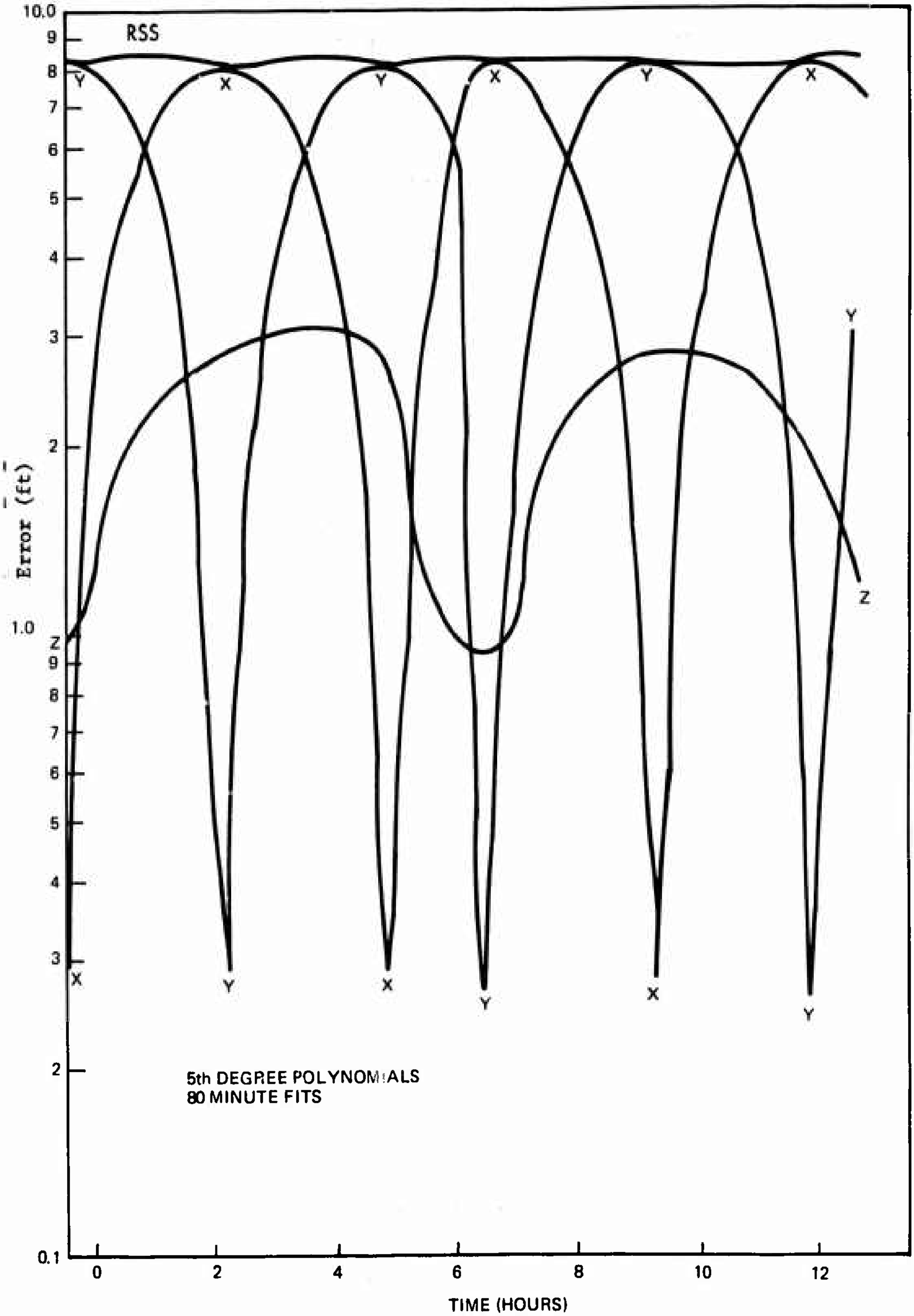

Figure 9-7 RSS and Component Fit Error Through One Orbit

A good estimate of the RSS fit error for a particular type of fit may be obtained by observing the error in the hardest-to-fit component over an interval where that component error attains its maximum. Figure 9-8, generated in this manner, shows how well different orders of polynomials may be expected to fit over various intervals of time. The length of the fit interval is determined by the satellite's message update frequency. Thus for worst case RSS fit errors of less than one foot, an update frequency of 30 minutes requires a 5th degree polynomial, 60 minutes a 6th degree, and 120 minutes a 7th degree polynomial.

4.6 Truncation Error

Because limitations exist on the downlink message size, truncation error can occur with any given representation form. The worst case truncation error occurs when the magnitude of the time variable and the magnitude of the corresponding coefficients simultaneously attain their maxima. The truncation error for an nth degree polynomial may be expressed as

$$\epsilon_T^2 = P(t) - \sum_{i=0}^{N} \left\{ c_i t^i + (\epsilon_{c_i} \cdot t^i)^2 + (c_i \cdot \epsilon_{t^i})^2 + (\epsilon_{c_i} \cdot \epsilon_{t^i})^2 \right\}$$

where

ϵ_T = Truncation error

ϵ_{c_i} = Error in coefficient i, c_i

ϵ_{t^i} = Error in the i^{th} power of t, t^i

Since $\epsilon_{t^i} = \binom{n}{i} \epsilon_t$, and since the coefficients are small enough to keep $c_i \cdot \epsilon_{t^i} < 1$ it is sufficient to minimize the simplified expression for truncation error $\epsilon_T^2 = \sum_{i=0}^{N} (\epsilon_{c_i} \cdot t^i)^2$

We wish to keep the total error small; ie, minimize $\epsilon^2 = \sum_{XYZ} \epsilon_F^2 + \sum_{i=0}^{N} (\epsilon_{c_i} . t^i)^2$ while simultaneously minimizing the number of bits required for representation in the data frame. ϵ_T was determined in the following manner. A sequence of

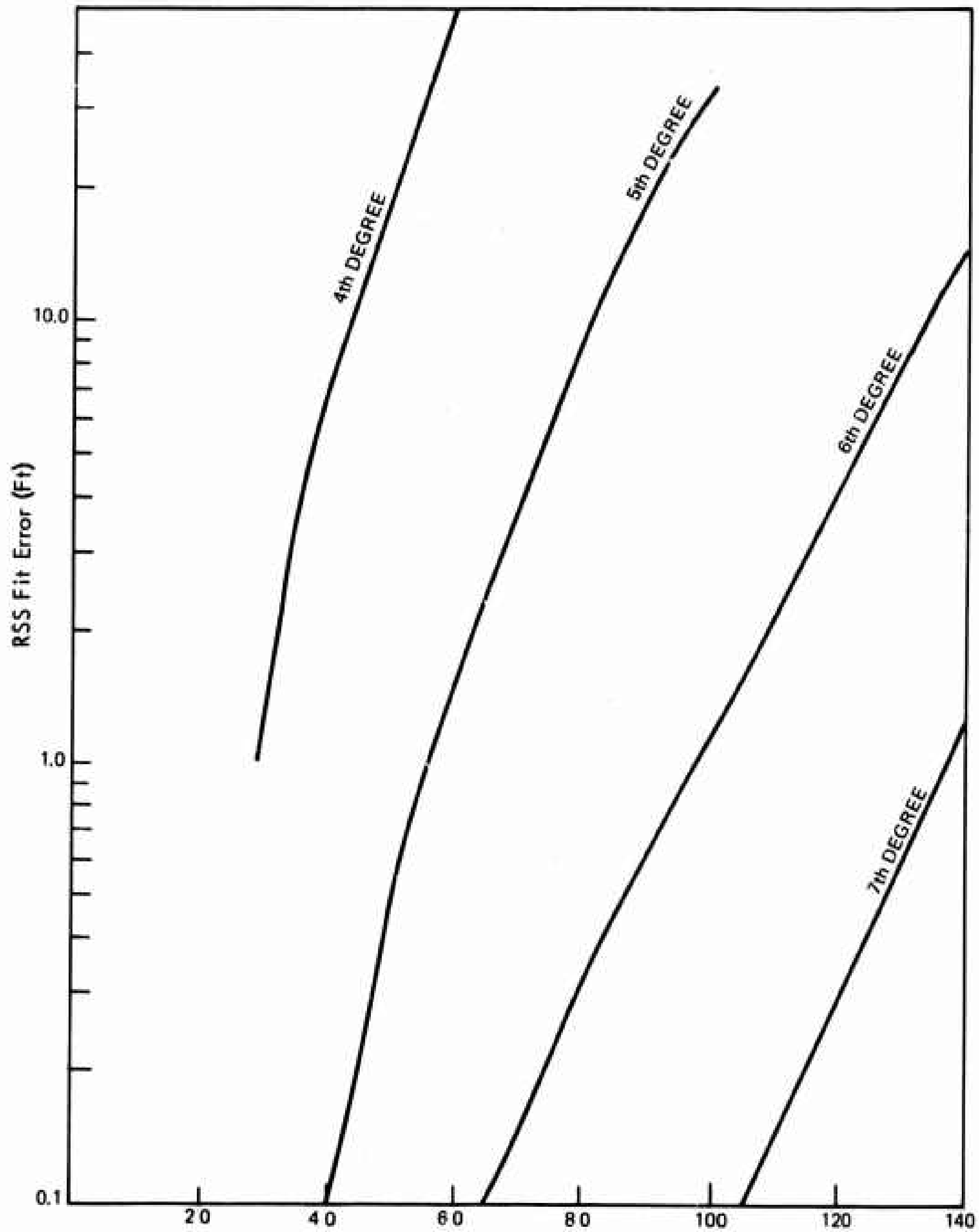

Figure 9-8 RSS Fit Error Over One Hard-To-Fit Interval

6th degree polynomials was fit to successive 30 minute data intervals. These intervals were displaced by 15 minutes until the entire orbit was covered. The largest magnitude for each coefficient was recorded. The quantization levels were determined so that the RSS error of the three fit errors and twenty-one equal truncation errors was approximately one foot. The number of bits required to represent the range of magnitude to the required precision was then computed.

The requirements for X, Y, and Z were virtually identical. The maximum and quantization magnitudes and bits required for each coefficient are shown in Table 9-17.

TABLE 9-17

Data Frame Requirements for
Satellite Ephemeris Representation

RSS Error = 0.8 Feet per 6th Degree Polynomial

Coefficient	Maximum Magnitude 4800 secs	Quantization Magnitude 4800 secs	Bits Required
a_o	7.4×10^{7}	1.4×10^{-1}	30
a_1	9.6×10^{3}	7.1×10^{-5}	28
a_2	5.6×10^{-1}	3.3×10^{-8}	25
a_3	3.5×10^{-5}	8.3×10^{-12}	23
a_4	1.7×10^{-9}	3.2×10^{-15}	20
a_5	7.4×10^{-14}	2.2×10^{-18}	16
a_6	3.1×10^{-18}	7.6×10^{-22}	13

The truncation error is controlled by manipulating the quantization level. Raising or lowering this threshold by a power of two raises or lowers the number of bits required for a single nth degree polynomial by n bits. Table 9-18 illustrates sample individual term ($a_i \cdot t^i$) truncation errors for the 80-minute polynomials with the resulting RSS error for three 5th degree polynomials.

TABLE 9-18

Individual Term Truncation Error τ and Resulting RSS Error ϵ: Three 5th Degree Polynomials

τ	ϵ^2	RSS ϵ
0.1	0.18	0.43
0.2	0.72	0.85
0.3	1.6	1.27
0.4	2.9	1.70

The total representation error may thus be controlled by altering the degree of precision used in transmitting the coefficients. A lower bound on this error is given by the RSS fit error. Table 9-19 and Figure 9-9 give the accuracy and bit requirements for four data update frequencies.

TABLE 9-19

Performance Measures for Several Data Update Frequencies

FIT SPAN		POLYNOMIAL DEGREE	RSS ERROR		NUMBER BITS REQUIRED
			Fit	Total	
Update Interval	Overlap				
15	15	4	1.2	1.8	320
15	20	5	0.03	0.8	385
30	15	4	10.1	11.0	300
30	20	5	0.5	1.1	426
60	10	5	3.7	4.1	415
60	20	6	0.3	0.9	465
120	20	6	13.5	13.7	513
120	20	7	0.8	1.2	550

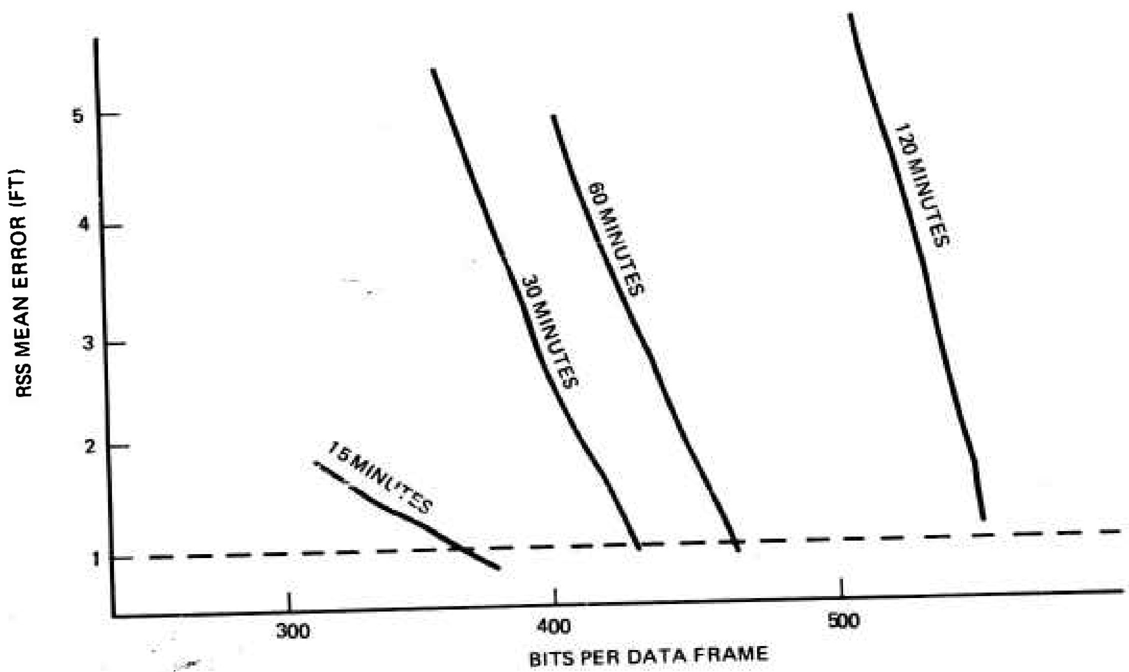

Figure 9-9 Representation Error vs Data Frame Size

4.7 Scaling Effects

The position of the zero of the polynomial has impact on both fit error and number of bits required for representation. The multiplication of the time variable by a constant makes relatively little difference. The results shown in Table 9-20 were generated from polynomials valid for $-1 \leq t \leq 1$. The data for generating a particular polynomial was taken over the stated number of seconds; time was effectively transformed from $0 \leq t \leq 4800$ to $-1 \leq t \leq 1$. Some transformation was necessary due to exponential overflows in computations using time in seconds.

Table 9-20 gives empirical justification for the particular scaling used. The magnitude of t does not impact fit accuracy or number of bits required. Theoretical justification may be found in the appendix. The net result is that proper scaling has advantageous effects on both fit error and representation size. The scaling used is virtually transparent to the user in evaluating the polynomial.

TABLE 9-20

Effects of Scaling Techniques on Performance Measures

	Average Residual	Standard Fit Error	Bits For Representation
(-2, 0)	.0988	.147	165
(-1.5,.5)	.0950	.142	155
(-1, 1)	.0899	.132	143
(0, 2)	.0941	.161	160

4.8 Impact on User Equivalent Range Error

The above discussion has been based upon RSS mean errors. The impact of ephemeris representation errors on user equivalent range errors, is, however, most efficiently studied by using the standard error of fit or RMS error.

User equivalent range error, E (based on satellite representation errors only), is given by

$$(1) \qquad E = \sqrt{TR\ (J)} \big/ GDOP$$

where

$$(2) \qquad J = A^{-1}\ (BQB^{T})\ (A^{-1})^{T}$$

and where

TR denotes the trace function

J is the covariance matrix of user position and clock offset estimation errors due to ephemeris representation errors

A^{-1} is a matrix giving the sensitivity of user position and clock offset estimation errors to ranging errors

Q is a covariance matrix of representation errors

B is a matrix giving the sensitivities of ranging errors to representation errors

GDOP is the user's geometric dilution of precision

A conservative estimate of Q is that it is a diagonal matrix whose diagonal elements are all equal to the maximum standard error encountered in any one coordinate (considering all satellites). Let this maximum standard error be defined as .

$$(3) \qquad J = A^{-1}\ (B\ \sigma^{2}\ I\ B^{T})\ (A^{-1})^{T} = \sigma^{2}\ A^{-1}\ (A^{-1})^{T}$$

since the rows of B consist of unit slant range vectors which vhen dotted with themselves become unity. Therefore,

$$(4) \qquad TR(J) = \sigma^2 \cdot GDOP^2$$

so that E, the ephemeris representation error contribution to user equivalent range error, is merely σ, the maximum standard error of fit.

For sixth degree polynomials which are updated once every hour, the maximum standard error of fit was found to be approximately one foot. The contribution to user equivalent range error with this form of representation is therefore less than one foot.

4.9 Appendix

4.9.1 Minimum Variance Polynomial Filter

The position function is expressed as $X(t) = \alpha(t)'\beta$, where $\alpha(t)'$ is a row vector $\alpha(t) = (1, t, t^2, \ldots t^n)'$ and $\beta = (a_o, a_1, a_2 \ldots a_n)'$ is the vector of polynomial coefficients.

The coefficients are generated by the matrix equation

$$\hat{\beta} = (A^1 Q^{-1} A)^{-1} A^1 Q^{-1} \underset{\sim}{y}$$ where

$\hat{\beta}$ is $(n+1) \times 1$ vector of best estimates for polynomial coefficients

y is mxl vector of data points

Q is mxm covariance matrix showing measurement uncertainity of data y

A is the mx(m+1) data coefficient matrix $\begin{bmatrix} 1 & t_1 & t_1^2 & \ldots & t_1^n \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ 1 & t_m & t_n^2 & \ldots & t_m^n \end{bmatrix}$

such that

$$A\hat{\beta} + \underset{\sim}{\epsilon_y} = \underset{\sim}{y}$$

$\underset{\sim}{\epsilon_y}$ is the mxl vector of residual fit errors.

The minimum variance estimator minimizes the magnitude $\|\epsilon_y\|$ of the residual errors. It is in this sense that $\hat{\beta}$ is the optimal set of coefficients. In the event that the uncertainty in each observation is equal, the estimation formula reduces to $\hat{\beta} = (A'A)^{-1} A^1 \underset{\sim}{y}$.

A major computational problem with using the polynomials 1, t, t^2, t^2.... is that, even when $Q = \sigma^2 I_m$, the (n+1) X (n+1) A' A matrix must be inverted. This problem may be avoided , and many theoretical analysis benefits will be realized, by using a set of orthogonal polynomials.

The Legendre polynomials solve the inversion problem. Denote by P* the space of orthogonal polynomials. By using an A* matrix with orthogonal columns, the $A^{*T} A^* = I$. The solution procedure then becomes $\hat{\beta}^* = A^{*T} y$. The inverse of the transformation T: P $\rightarrow$ P* gives $\hat{\beta} = T^{-1} \hat{\beta}^*$, which means that the procedure yields coefficients for the more familiar polynomials 1, t, t^2.... The orthogonolization procedure depends on the particular values of the columns of A, so may not be generated until the observation times are known.

4.9.2 Error Sources and Sensitivities

Use of orthogonal polynomials enables one to analyze the effects of various model parameters. Number and spacing of data points, degree of the polynomial, and positioning of the origin within the observation interval are the parameters of primary interest. Constant spacing between data points is assumed for the analysis, and this poses no problem for the data generation. Space numerical problems may result from this constant spacing, this requirement may be relaxed for operation. The results of the orthogonal polynomial analysis obtain also with the classical least squares approach; the only substantial difference is greater computational error in the classical mode.

We will first look at minimization of random error, or variance reduction. The basic assumption is that observation errors are of zero mean and constant variance. Significant results include:

- number of data points: Variance about the parameter estimate goes to zero as the number of data points increases. In fact $\sigma_i^2 \propto \frac{1}{L}$, where i is the power of t (the ith coefficient), and L is number of data points.

- sampling rate: Increasing the sampling rate while keeping the total number of points constant increases the variance of the output errors over the smaller interval. Increasing the sampling rate over a constant time period, thereby simply increasing both the density and the number of points, reduces the variance. The critical factor is L. For $\frac{T_i L_i}{T_o L_o} > 1$ where i is a modification on the null policy, variance will decrease.

- degree of polynomial: Since the variance of the estimate is the trace of the non-negative definite covariance matrix, higher degree polynomials necessarily increase the error.

- location of the independent variable: The orthogonal polynomials are constructed such that all their zeros are within the observation interval. Therefore predictions outside this interval cannot be relied upon; the higher the degree, the worse extrapolative power. Half of the polynomials have zeros at the midpoint of the interval. Therefore estimation error is smallest in the middle, increasing as much as an order of magnitude toward each side. The rapid increase in uncertainty begins at the endpoint.

Systematic errors result from the mismatch between the model and the true process. The impact on systematic error of the primary parameters are as follows:

- degree of polynomial: Since virtually any function may be expressed as an infinite power series increasing the order of the polynomial will both

provide a better fit and reduce the amount of smoothing done. However, the order of the polynomial is trictly bounded by the number of data points, and is in practice bounded by degree of approximately one-fourth that number.

- location of independent variable: As above, the fact that all the zeros of the orthogonal polynomials be within the observation interval suggests that systematic error is minimized near the middle of that interval. Higher order polynomials result in smaller intervals of larger error about each endpoint.

- number of data points: Each term of the systematic error function is increasing with the number of data points. Thus, for fixed polynomial degree and sampling rate, systematic error is minimized by minimizing the number of data points.

- data sampling rate: For a fixed number of data points, high sampling rates minimize systematic errors; any power series may be adequately approximated by a polynomial of given degree if the interval is small enough. If sampling rate, and therefore number of data points, is increased over a given interval of time, the systematic error approaches an astymptotic value. Therefore, after a certain point the fit will not improve, but the additional data points will adversely impact the error.

4.9.3 Impact on Problem Formulation

Numerical formulation of a curve fitting routine may take advantage of the above results in several ways.

1. Balancing of systematic and random errors. By realizing the effects of the major contributors to the overall error, a balance may be struck between the two types of error. For example, if representation accuracy over a given interval is the goal, the contributions from each error type would be set equal. On the other hand, if a long term fit with a small order polynomial were required, the random error terms could be virtually ignored.

2. Trend removal. If there exists a nominal trajectory, which is reasonably close to the actual data, additional computational benefit may be realized. The data used by the filter will then be of smaller magnitude, enabling a reduction in systematic errors. This may enable us to

   a. Attain greater accuracy
   b. Reduce the degree of the filter
   c. Lengthen the observation interval

5.0 RELATIVE NAVIGATION ERROR

Relative navigation error may be defined in several ways but most commonly is defined to be the accuracy with which a user can determine his location relative to: 1) previous estimates of his location, 2) another user, 3) a ground station, or 4) his own home base. All four definitions, or situations, have the characteristic that certain common error sources can be expected to cancel.

The definition of relative navigation error, as used here, will be associated with 1) namely, the accuracy associated with one user being able to make repeated estimates of a fixed location over an extended period of time. That is, we will seek the expected deviation of a user's navigation estimate from previous navigation estimates and ask how this changes with time.

At time t_1, a user makes an estimate of his position and clock offset, $\hat{\underline{X}}_1$ (ie, latitude, longitude, altitude, and range bias), which deviates from his true location and clock offset, $\underline{X}$, by the amount $\delta\hat{\underline{X}}_1$. At time t_2 this same user makes another estimate of his location and clock offset, $\underline{X}_2$, which this time deviates from his true position and clock offset by the amount $\delta\hat{\underline{X}}_2$. We now ask the question: What is the expected deviation of $\delta\hat{\underline{X}}_2$ from $\delta\hat{\underline{X}}_1$?

In an attempt to answer this question, we will assume that the times t_1 and t_2 are such that the satellites are in identical positions relative to the user so that his geometric dilution of precision remains constant. We will also assume that the user is stationary with respect to the earth and that the only errors in his estimates are due to ephemeris and clock errors.

Now if $\delta\hat{\underline{X}}_1$ is the user's navigation estimation error at time t_1 and $\delta\hat{\underline{X}}_2$ is the user's navigation estimation error at time t_2, then the expected difference between these two errors is given by:

$$Q = E\{(\delta\hat{\underline{X}}_1 - \delta\hat{\underline{X}}_2)(\delta\hat{\underline{X}}_1 - \delta\hat{\underline{X}}_2)^T\} \tag{1}$$

$$= E\{\delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_1^T + \delta\hat{\underline{X}}_2 \delta\hat{\underline{X}}_2^T - \delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_2^T - \delta\hat{\underline{X}}_2 \delta\hat{\underline{X}}_1^T\}$$

$$= E\{\delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_1^T\} + E\{\delta\hat{\underline{X}}_2 \delta\hat{\underline{X}}_2^T\} - E\{\delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_2^T\} - E\{\delta\hat{\underline{X}}_2 \delta\hat{\underline{X}}_1^T\}$$

where $E\{\ \}$ is the expected value operator and where

$E\{\delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_1^T\} = \varphi_1$ = covariance matrix of the errors in the user's position and clock offset estimate at time t_1.

$E\{\delta\hat{\underline{X}}_2 \delta\hat{\underline{X}}_2^T\} = \varphi_2$ = covariance matrix of the errors in the user's position and clock offset estimate at time t_2.

$E\{\delta\hat{\underline{X}}_1 \delta\hat{\underline{X}}_2^T\} = \varphi_{12} = \varphi_{21}^T$ = covariance matrix of the user's errors at time t_1 with this errors at time t_2.

Equation (1) can therefore, be written in a simpler form, namely,

$$Q = \varphi_1 + \varphi_2 - \varphi_{12} - \varphi_{21} \tag{2}$$

The first two terms of (2) are respectively the individual estimation errors at times t_1 and t_2 which include the effects of common error sources such as satellite positions and clock offsets. The last two terms represent the correlations of the errors at t_1 with the errors at t_2. Since these correlations manifest themselves through error sources which are common to the two estimates, they can be expected to reduce the contributions to Q from the first two terms.

For example, if $t_1 = t_2$ (i.e., two simultaneous estimates) and the only error sources present are satellite errors (i.e. no clock or receiver noise), we should expect the errors in these two estimates to be perfectly correlated so that identical estimates would be made (This does not say, however, that these two estmates do not contain errors). In this unique situation, we should expect the last two terms in (2) to exactly cancel the first two terms.

From simulation results of the distributed processing concept presented in section 2.0 above, equation (2) was evaluated using the WSMR user solution results at 3 and 27 hours from the end of the observation interval. Thus, t_1 = 3 hours and t_2 = 27 hours. The resultant Q prime matrix given below, thus represents the expected difference in WSMR position estimates (made 24 hours apart using the same data base, ie, the same satellite ephemerides and clock parameters) due to changes in satellite position errors and modelable clock errors over this time period. The results were obtained as follows:

The WSMR position and clock offset estimation error covariance matrix at 3 hours was

$$\varphi_1 = \begin{pmatrix} 56.8 & -32.6 & 113.9 & 57.6 \\ -32.6 & 73.1 & -21.4 & -8.2 \\ 113.9 & -21.4 & 1019.7 & 600.8 \\ 57.6 & -8.2 & 600.8 & 373.6 \end{pmatrix}$$

where diagonal terms from left to right represent variances in latitude, longitude, altitude, and range bias respectively. All numbers are in feet^2. For the errors at 27 hours (or 24 hours after the first estimate the estimation error covariance matrix was

$$\varphi_2 = \begin{pmatrix} 77.7 & -39.7 & 115.0 & 64.8 \\ -39.7 & 88.1 & 14.5 & 10.0 \\ 115.0 & 14.5 & 939.8 & 556.1 \\ 64.8 & 10.0 & 556.1 & 353.4 \end{pmatrix}$$

The covariances of the errors were

$$\varphi_{21}^T = \varphi_{12} = \begin{pmatrix} 64.9 & -34.5 & 102.4 & 533.3 \\ -36.5 & 78.8 & -0.9 & 2.3 \\ 125.4 & -4.4 & 951.2 & 544.5 \\ 66.6 & 1.4 & 566.3 & 351.5 \end{pmatrix}$$

Thus

$$Q = \begin{pmatrix} 4.7 & -1.3 & 1.1 & 2.5 \\ -1.3 & 3.6 & -1.6 & -1.9 \\ 1.1 & -1.6 & 57.1 & 36.1 \\ 2.5 & -1.9 & 36.1 & 24.4 \end{pmatrix}$$

If we now define a pseudo correlation matrix where the off diagonal terms are correlation coefficients and the diagonal terms are sigmas in latitude, longitude, altitude, and range bias respectively, we obtain

$$Q' = \begin{pmatrix} 2.2 & -0.311 & 0.132 & 0.204 \\ -0.311 & 1.9 & -0.132 & -0.204 \\ 0.132 & -0.132 & 7.6 & 0.969 \\ 0.204 & -0.204 & 0.969 & 4.9 \end{pmatrix}$$

The expected deviations in estimates of latitude, longitude, altitude, and range bias made 24 hours apart are therefore, 2.2, 1.9, 7.6 and 4.9 feet respectively.

The RSS of these navigation errors is 9.5 feet. Dividiing this by GDOP, 4.25, gives a relative ephemeris UERE contribution of 2.24 feet after 24 hours.

REPORT C 10

SIGNAL POWER MONITORING TECHNIQUES

REPORT C 10

SIGNAL POWER MONITORING TECHNIQUES

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1.0 BACKGROUND

At the request of SAMSO/Aerospace, WDL examined several possible techniques for monitoring (ie, measuring) the received power level of GPS satellite signals. This problem is substantially compounded by the use of the spread-spectrum modulation, and by the simultaneous presence of signals from several satellites all radiating on the same carrier frequency. The text of a letter from SAMSO to Philco-Ford WDL is quoted as follows: "To ensure that the proper level of power is being transmitted by the satellite, the monitor stations should measure and record the appropriate data. The following questions are submitted for your consideration. Preliminary response is required by 1 February with the final incorporated into the 28 February submittal.

a. How can the monitor station measure the received power level from the satellite with PN modulation activated?

b. What degree of accuracy would the measurement provide?

c. What is the impact on the design of the receiver or other monitor station components?"

During 1972/1973 WDL developed a high-precision received-signal-level measurement technique for the SCF (SGLS) receiving system; in addition to development and on-site testing of the RF hardware, a small minicomputer which controls the entire receiver calibration process has been developed, to be used as a companion adjacent to the RF equipment. This equipment has resulted in measurement errors of about 0.5 - 0.7 dB, for clear-channel signals having a distinct carrier well above the background noise level. Philco-Ford also developed an accurate radiometer for use with the SCF 46-foot TT&C subsystems. Both of these techniques are discussed briefly in this report.

Because of the relatively more complicated nature of the GPS signal measurement problem (ie, multiple signals, each of the spread-spectrum variety), a highly dependable and accurate technique for signal level monitoring has not yet evolved. The various subsections of this section record the consideration which were given to the signal level measurement problem. There is no direct way of satellite EIRP monitoring on orbit by a monitoring station. The next best technique is to measure the incident flux at the monitor station and compensate for range/antenna/atmospheric absorption effects. A measurement of received signal power cannot be made directly either, but can only be inferred from measurement of one or more receiver parameters such as AGC, ranging noise, or data error probability. Suffice it to say that the incident signal cannot be directly measured, but only ratio of incident signal-to-system noise power density. The total system noise has contributions from the monitor station front end, as well as from sources external to the monitor station itself (i.e., sky noise, man made noise, other satellite signals, etc.).

Measurement Parameters

C/N_o (system) can be inferred by measurement of range measurement variance (σ_r), data signal power to noise density ratio (E_b/N_o) and AGC level. The σ_r measurement is likely the most sensitive measure of received signal quality, and a comparison of σ_r from the calibration source (Technique 2) with σ_r from the measured satellite is likely the most accurate technique. E_b/N_o measurement depends partially on σ_r and the system noise, and AGC is

influenced by monitor stations RF/IF gain variation as well as σ_r. This parameter (σ_r) can be calculated by means of a number of sequential pseudo-range measurements, removing the motion parameters of the satellite, and computing the variance. Careful calibration of σ_r versus C/N_o is a prerequisite for accurate calibration of C/N_o. The determination of σ_r may be made at the master station by means of suitable computation on sequential pseudo-range measurements relayed by the monitor station.

1.1 MEASURMENT METHODS

A number of techniques for performing this monitor function are enumerated below.

1. Measurement of $C/N_{o(Syst)}$ for each satellite.
   (Direct Measurement)
2. Measurement of $C/N_{o(Syst)}$ for each satellite and compare with $C/N_{o(Syst)}$ from some stable, calibrated signal simulator
   (Comparison Measurement)

   The signal simulator injects into the monitor station antenna.

Technique 1 - Suffers from possible variations in monitor station health status (noise figure, alignment etc.) and may introduce considerable uncertainty into the measurement. The radiometer method of measuring the received power is an example of Technique 1.

Technique 2 - Will wash out the effect of degraded monitor station health and will include the effects of environmental noise. This is the preferred technique. Careful calibration of the monitor station antenna gain over the hemisphere of incident signal directions (including that from the calibration source) must be performed and used in the determination of satellite output power. The constraints on location of the calibration transmitter are the following; near enough, to not suffer significant atmospheric absorption, far enough, to be in the monitor station antenna "far field." Stability of the calibration source ERP is essential and instability contributes directly to error in satellite ERP measurement. The technique for calibration is summarized below.

1. Calibration signal injected into monitor station antenna far field at known power level.
2. Monitor station periodically locks to calibration signal and sends pseudo-ranges to master station.
3. Monitor station takes many sequential measurements of pseudo-range from direct satellite and sends these to master station.
4. Master station computes EIRP from σ_r (satellite) to σ_r (calibration) ratios, takes into account effects of satellite antenna gain in direction of monitor station, range loss, predicted atmospheric absorption, monitor station gain in direction of satellite and calibration source.

An alternative method of making the comparison between the calibration signa signal and the incoming satellite signal is the use of calibrated AGC voltages.

1.2 Radiometer Technique

The noise-like nature of the GPS satellite makes the radiometer method of measuring power appear reasobable for measuring the received signal strength from the satellites. The radiometer receiver is a 20-MHz bandwidth device, which has a noise amplitude detector and an integrator at the output. The input is switched between two courses of accurately known noise power for calibration and then between the unknown noise source and the background noise. The integrated noise powers are recorded on a strip chart, so that the temperature differences can be scaled from the chart. This method measures differences and as a result, the receiver noise is eliminated from the measurement.

To measure power of a satellite signal, it is first necessary to calibrate the antenna by receiving power from a radio star having well established flux density. The second step is to receive power from the satellite and compute its power by comparison with the known star flux.

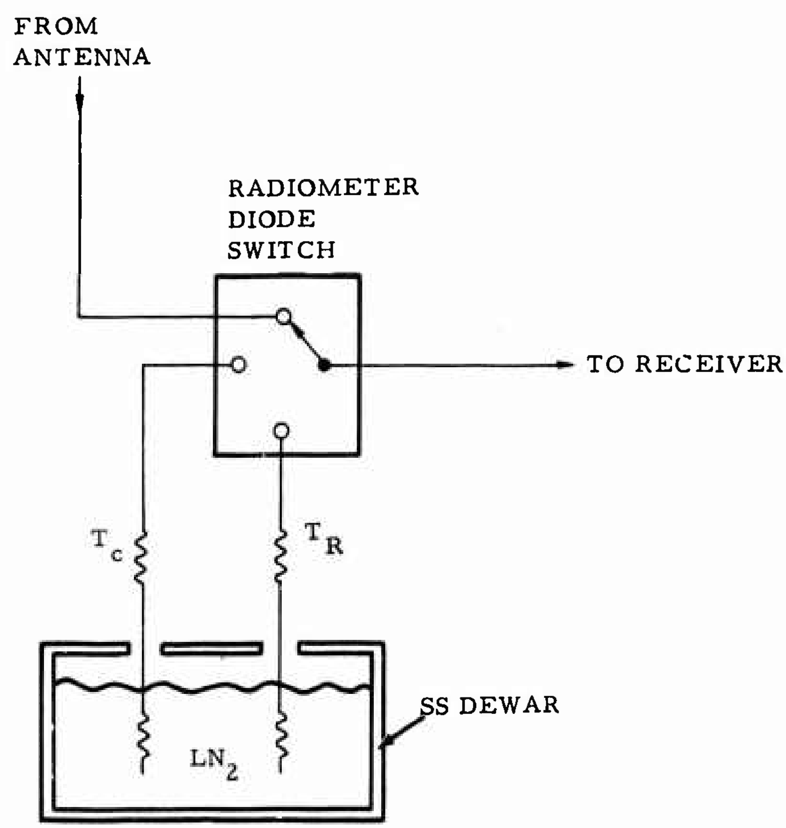
The critical elements of the radiometer system are the cold and hot noise sources, the antenna, the radiometer input switch, and the output noise

detector. Of these the radiometer switch is the most critical. A typical unit is a diode-switch constructed of strip-line, and carefully tuned to eliminate variations in loss resulting from high VSWR. The cold noise sources are carefully constructed of special material to withstand exposure to the low temperatures created by liquid nitrogen. These features are diagrammed in Figure 10-1.

Accuracy of the radiometer depends on the uncertainty in measuring the losses between switch and its inputs, in the switch itself, recorder linearity and other factors. In the radiometer used in the SCF the total RMS errors amount to $\pm 4.5^{\circ}$.

Antenna gain measurement accuracy depends on adequate gain for the antenna, so that star temperature rise values of at least 50 K are obtained. Antenna gains of 45 to 48 dB with low noise front ends will provide this performance; smaller antennas will not. Temperature rise is shown as a function of antenna size for a 140 K noise temperature system in Figure 10-2. With a 47-dB gain antenna, such as a 60-foot parabolic reflector working at 1575 MHz, the star temperature rise has been computed as 48.4 K. When the 4.5 K accuracy is compared to that value, the error is 9.3%, amounting to 0.42 dB.

* 46-foot TT&C Subsystem Design Analysis Report, WDL-TR 4294, 30 Oct. 1970



T_c = Calibrate Temperature Load
T_R = Reference Temperature Load

FIGURE 10-1 Radiometer Switch

It should be kept in mind that the radiometer method, the calibrated receiver method described in the following section, and the statistical analysis of the range measurement variance σ_r^2, are all methods of comparing accurately-known test signal power levels to the unknown received signal power levels. With the radiometer star flux serves as the standard for comparison and with the calibrated receiver method the test signal is man-made.

The radiometer can also be used in the "Y-factor" mode which measures the ratio of (signal plus noise) to noise. This method first measures the system noise and then measures the (S + N)/N ratio from which received power can be computed. Figure 10-3 shows the values of Y-factor expected with several receiver noise temperatures as a function of antenna size. Low Y-factors reduce the accuracy, and it is general practice to avoid values less than 2 dB, which lead to errors in excess of 2% in power when the error in Y factor is ± 0.1 dB.

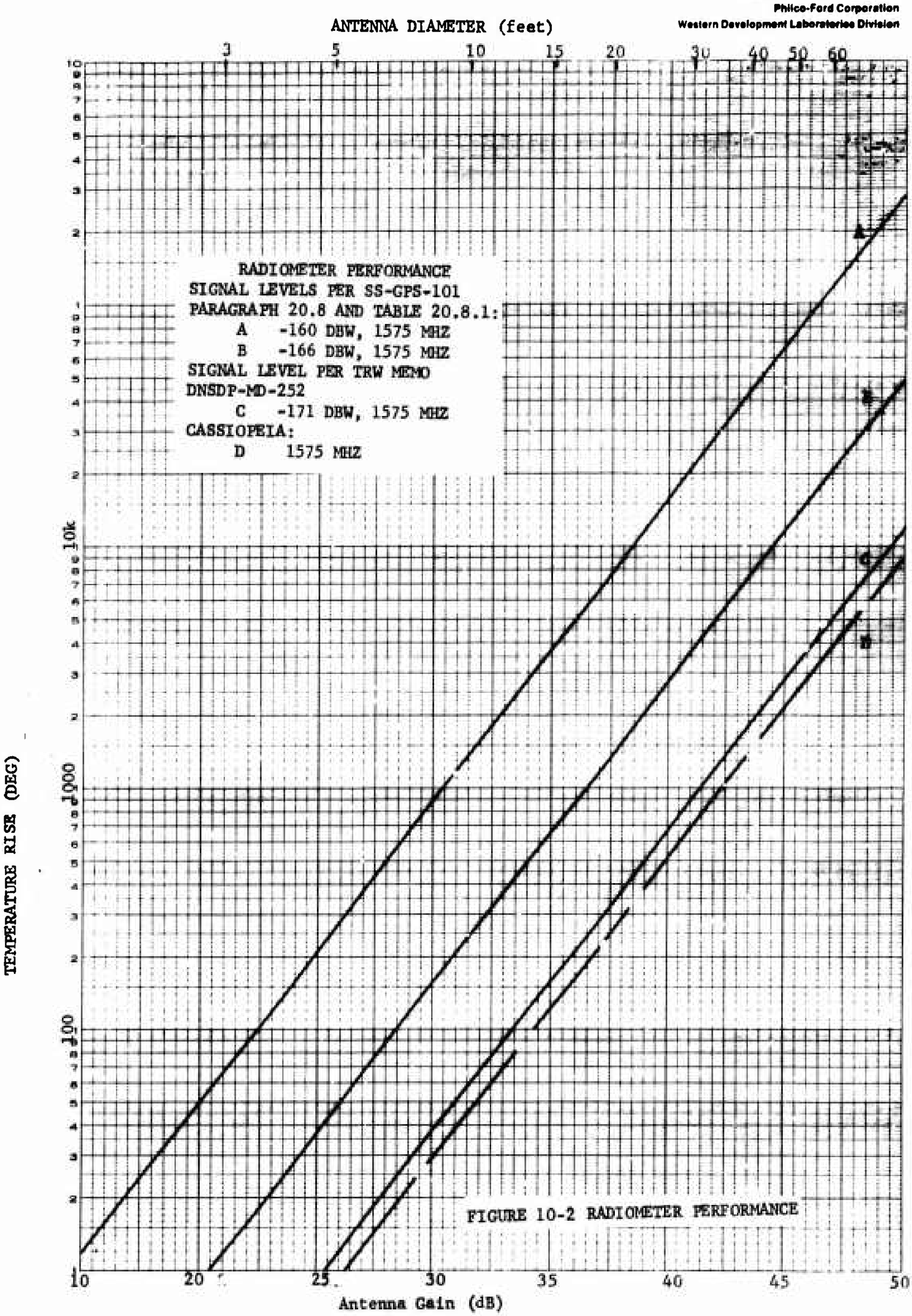


FIGURE 10-2 RADIOMETER PERFORMANCE

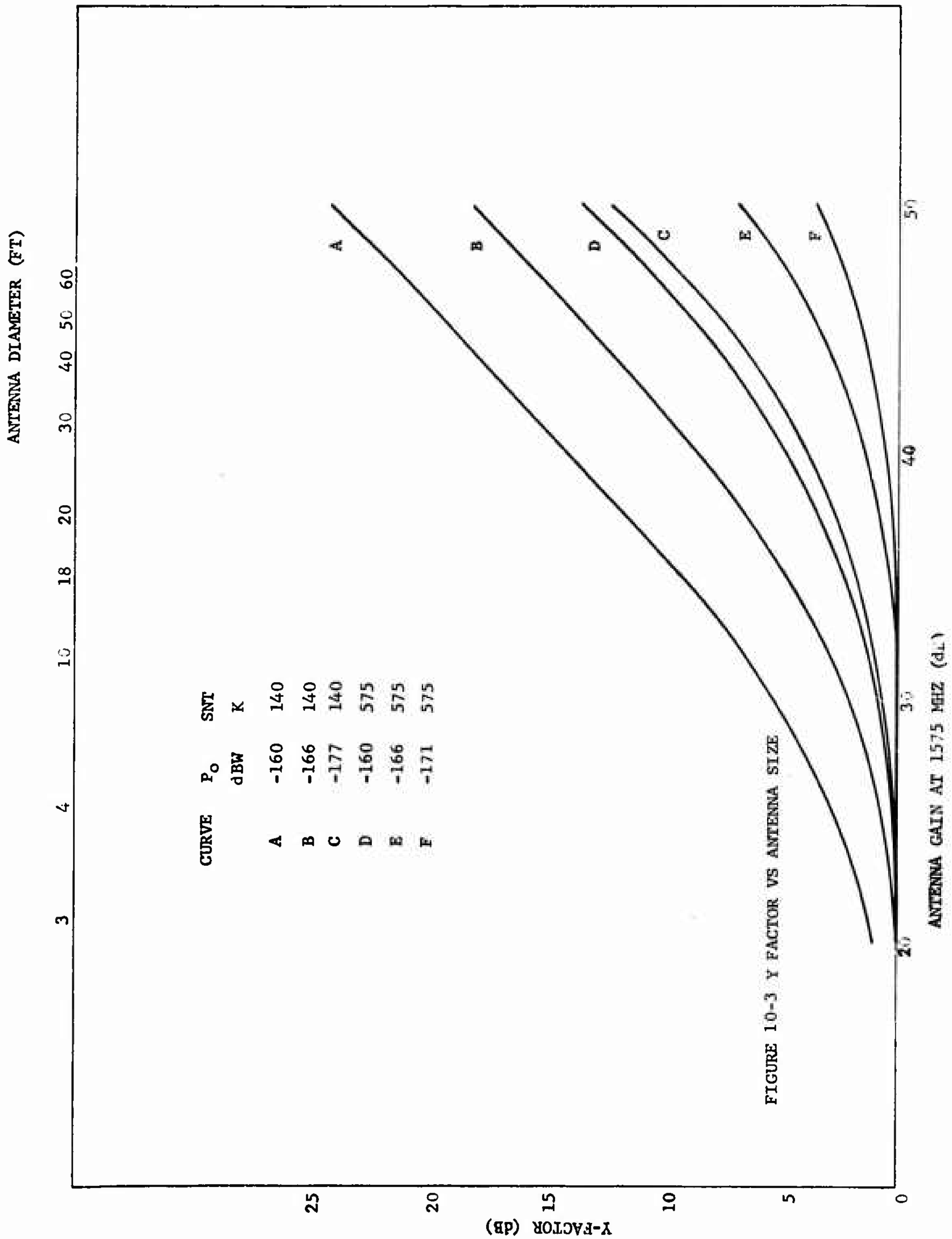
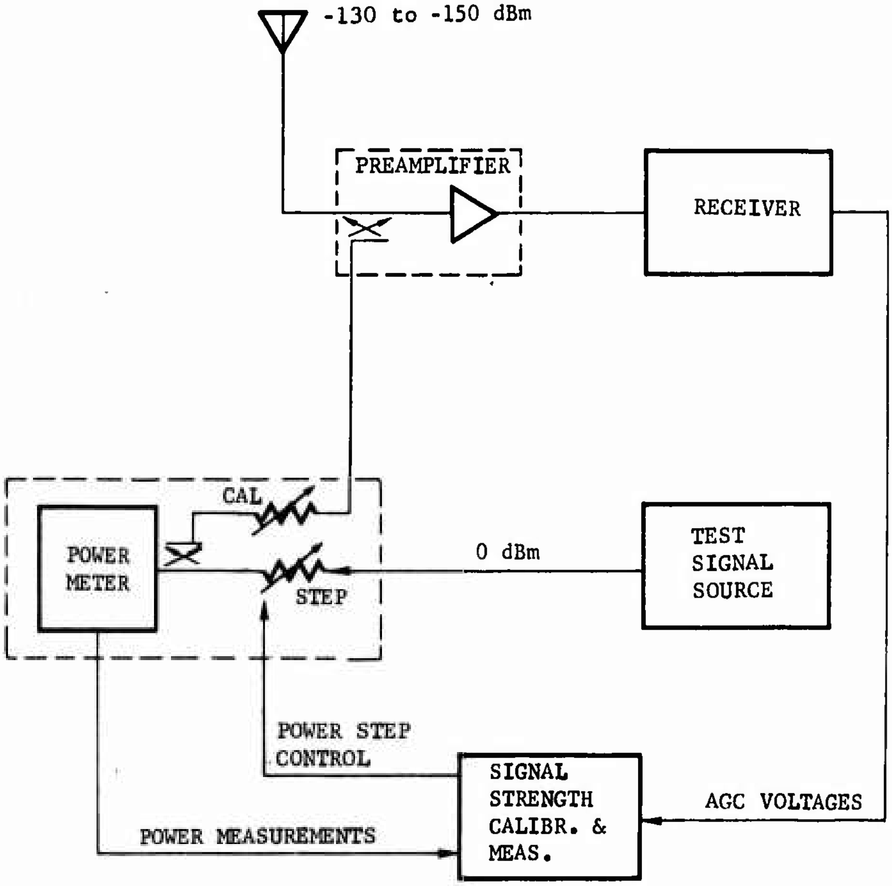


FIGURE 10-3 Y FACTOR VS ANTENNA SIZE

1.3 Calibrated Receiver Technique

The studies which led to the development of the signal strength measuring technique described hereafter show that the automatic gain control (AGC) voltage developed in a radio receiver is a predictable function of the receiver input signal power. The relationship is usually semilogarithmic, because of the need to control the receiver gain over wide dynamic ranges. Experience in the Satellite Control Facility (SCF) has demonstrated the practicality of the technique described here.

Figure 10-4 shows, in very much simplified form, the signal strength measuring equipment. The equipment consists of two basic units, one of which measures the test signal power and supplies a known fraction of the measured power to the receiver input. The other unit is the control device which sets test signal levels, receives and stores the test levels and the receiver AGC voltages which result from the application of the known test signal levels to the receiver input during the calibration cycle. When the level of an incoming satellite signal is to be determined, the control unit interpolates the receiver AGC voltage betwen the two adjacent calibration points stored in its memory and outputs the signal strength in appropriate units. The control unit can be a dedicated device, or its function can be assumed by the monitor station computer. If the dedicated device approach is selected, then the SSC must have an interface with the MON computer.



RECEIVER INPUT (dBm)	AGC VOLTAGE
-127	-6
-128	-5.8
-129	-5.6
⋮	⋮
-157	-0.1

FIGURE 10-4 Signal Strength Measuring Method

The power levels used to calibrate a radio receiver AGC voltage in terms of input power are much lower than the lowest power measured by even the most sensitive RF power meter. The signal strength calibration unit, therefore, provides a large attenuation factor from the measured test signal level to the test signal level applied to the receiver input. Thus the signal can be measured at levels between 0 dBm and 30 dBm, and injected into the receiver input port at levels between -125 and -155 dBm. In effect, the method calibrates the receiver for use as an accurate RF power meter specifically adapted to measuring signals in its own power input range.

It is now appropriate to consider the use of the technique just described for measuring the power levels of spread spectrum signals. The signals applied to the receiver input are far below the system noise threshold, but after the spectrum of such a signal has been collapsed by the PN demodulator into its original narrow-band form, the signal is processed in the same way as any other signal. Specifically, the narrowband signal is demodulated by an IQ-loop demodulator to extract the 50 b/s data signal. The level of the data signal demodulated by a coherent amplitude demodulator is an analog of the input signal strength, which the receiver utilizes as an AGC voltage.

The detail design of the Type IV, continuous 4-channel receiver has not yet been completed, and as a result of design constraints imposed by the code acquisition and lock circuits the AGC characteristic may prove unsuitable for SSC operation, although the probability of that happening is low. In the event that the User receiver AGC characteristic is not amenable to SSC operation then an auxiliary receiver having a suitable AGC system must be provided. The receiver would hopefully be able to use the User Type IV receiver's replica codes for spectrum compression, but again this hinges on the low level design details of the Type IV receiver.

Evaluation of the accuracy of prototype signal receiver calibration system was performed in the SCF TRACKING STATION, NHS. The results are presented in WDL-TR5123, 20 February 1973, "Evaluation of Signal Strength Calibration and Noise Temperature Measurement Equipment. They are summarized as follows:

Repeatability over 70 to -140 dBm curve, 24-hour period. Overall measurement accuracy in a 20 dB window	±0.7 dB
20 dB window calibration repeatability over 1-hour period	±0.2 dB

20 dB window calibration repeatability

over 24-hour period ±0.5 dB

2.0 EVALUATION OF SATELLITE EIRP

A preliminary estimate of the accuracy with which ground station measurements can determine satellite EIRP has been made assuming a calibrated receiver technique is used. The factors taken into account are:

Slant range - accurate knowledge of slant range permits working back to determine EIRP Error for range = 0.

Monitor Station Radiation Pattern - The MS antenna has a radiation pattern which varies with azimuth and elevation. Although it would be possible to calibrate the antenna gain within a hemisphere, the use of a directional antenna pointed by the ULS slave bus, or physically mounted on the ULS uplink antenna, can provide better accuracy. The calibration is good to ±0.3 dB.

Satellite Attitude - The effective satellite antenna gain will depend on the location of the monitor station in the field of the satellite antenna. This can be determined from the satellite's attitude and location with respect to the monitor station. Again, the actual value will depend on factors, which have not been established yet, but which may be amenable to

analysis at a later date. In any case, with four monitor stations observing signal strength during a pass, there is a good probability that the EIRP can be established. No firm assignment of error value is possible for satellite attitude, but for the purpose of preliminary evaluation we can use ± 1.5 dB.

Test Signal Coupling Accuracy - The coupling factor between the level at which the signal is measured and that at which it is injected can be calibrated accurately by direct substitution of known signal levels into the receiver inputs. Test signal injection at the receiver input is less satisfactory than injection in the signal path. The error factor for coupling accuracy is assigned a value of ± 0.1 dB.

Radome Losses - Radome losses for dry weather conditions can be included in the calibration factor for test signal coupling. However, with rain and snow accumulations on the radome it could be necessary to recalibrate the system.

Precipitation - Losses due to precipitation are not serious at L-band, with 0.02 dB/km for 100 mm per hour rainfall cited by "Reference Data for Radio Engineers, Fifth Edition". No assignment of error is needed for preceipitation.

Receiver Gain Stability - At this time nothing is known about the stability of the receiver gain with temperature and passage of time. The obvious effect of gain variation will be to diminish the time spans for which a calibration will

be considered valid. Past experience in SCF receivers indicates that the calibration should hold within ±0.5 dB over 24 hours. With an allowance for unknowns, an error figure of 0.5/8 hours will be used at present.

Code Correlation - The amplitude of the AGC is a function of the code correlation factor, and therefore it is degraded at low signal levels when the incoming code is contaminated by noise. The statistical properties of the satellite code and the receiver replica code are also factors which can change the AGC voltage as a function of incoming signal level. For the present, however, the effects of degraded signal to noise ratio will be assumed to be the same for the calibrating test signal as for the satellite signal, ie, most of the errors due to degraded SNR will be calibrated out. An allowance of 0.5 dB will be assigned to residual error due to degraded correlation.

TABLE 10-1

SATELLITE POWER MEASUREMENT ACCURACY

SSC Stability over 24 hours	±0.5 dB
Range	0
Monitor Antenna Calibration	±0.3 dB
Coupling Accuracy, Test Signal	±0.1 dB
Randome Loss (Calibrated out)	0
Precipitation	0
Receiver gain over 8 hours	±0.5 dB
Correlation	±1.5 dB
TOTAL	±2.9 dB

If the radiometer method is used in place of the calibrated receiver method, receiver gain stability will not be a factor, with an improvement of 0.5 dB, and SSC stability will also disappear, with an overall improvement to a total inaccuracy of about 1.9 dB.

3.0 IMPACT ON MONITOR STATION DESIGN

Technique 1, the radiometer receiver, adds to the MS all the necessary equipment for received signal level measurement. The new equipment requires one rack of receiver and recorder equipment, and a high gain receiving antenna. There would be an impact on the site processor to point the antenna if the radiometer is not co-located with the ULS where antenna slaving is required in any case. The need to track radio stars creates an impact on the tracking computer software, as well. The radiometer equipment must be attended by an operator who maintains the $L\text{-}N_2$ level, manipulates the receiver controls, reads the strip charts and computes the received signal levels.

Technique 2 requires interfaces from the User receiver in the MS to the calibrating equipment and requires a satellite-tracking antenna in addition to the MS omni directional antenna. There are also interfaces with the site data processor to control and record signal strength, record AGC levels, and perform look-up and interpolation functions during actual

measurement of incoming signals.

The SSC head is in a weatherproof enclosure approximately 1x1 1/2x2 feet, but if need be, can be made smaller. The size used to date is the result of packaging the unit in a parametric amplifier power supply enclosure mounted in the SCF antennas in the space formerly occupied by the power supply. The SSC unit in the receiver rack can be packaged behind a panel two rack units high (3 ½ inches), or it can be integrated into the BITE. The most satisfactory way to couple the test signals into the receiver is to radiate them in the vicinity of the monitor station antenna.

This has the advantage that it includes the antenna, coaxial connectors, and coaxial cables in the calibration loop. It will also tend to calibrate out the effects of snow and ice accumulations on the antenna or the radome. The major disadvantage is that the space in the vicinity of the radiator and the monitor station antenna must be maintained constant, ie, no new sheet metal ducts on the roof, for example. An ample ground plane will be provided for the antenna to establish a constant environment. The test signal may also be coupled into the receiver via a directional coupler inserted in the coaxial transmission line running from the antenna to the receiver input port. This method has the advantage of constancy of

coupling, but it excludes the monitor station antenna and surroundings from the calibration loop. Adjustment and calibration of the coupling from the test radiator to the monitor station antenna is performed using direct substitution of signal sources at the receiver input. This references the signal strength to the input of the preamplifier, which is then projected to any other point in the system.

The SSC head contains attenuators and directional couplers as well as the crystal diode power sensor. The DC voltage produced by the crystal diodes in response to an RF input power is conducted to the SSC logic, where a chopper-stabilized dc amplifier raises the voltage to usable levels, and an a/d converter digitizes the level. The resulting signal then represents the receiver input levels plus the coupling factor from the test signal line to the receiver input. The true receiver input level is then computed by summing the indicated test signal power and the coupling factor. The SSC head should be located as near to the test radiator as practical to minimize the loss between the measuring point and the injection point and hence the possible variation in that loss.

Each channel of the four channel receiver produces an AGC voltage which is the analog of the signal strength in that channel. Each of the AGC voltages is converted to digital form with a logic interface compatible with that of the computer. The computer scans each of the four AGC

voltages in turn, and stores the values for later use.

4.0 PROCEDURES

4.1 Radiometer Measurements

The radiometer is assumed to be ready to operate, with the loads at rated temperature. In simplified form, the procedure is:

1. Switch the input to the reference (77 K) load and record noise temperature on strip chart.
2. Switch the input to the calibrate (120 KO load, and record noise temperature.
3. Direct the antenna to sky adjacent to a radio star, but far enough off that star noise does not appear in the receiver input.
4. Record the background noise temperature.
5. Direct the antenna so the radio star is on axis and maximum power is received.
6. Record the star noise temperature on the strip chart.
7. Direct the antenna to a satellite and repeat steps 3 to 6.
8. Compute satellite received flux by comparison with flux received from known radio star.

4.2 Calibrated Receiver Measurement

The calibrated receiver technique can be operated with no human attendance. The simplified steps in making the measurement are:

1. Generate a test PN signal and radiate it into the station antenna.
2. Set the test signal level to the maximum expected signal strength
3. After PN code acquisition measure signal power and AGC voltage.
4. Store Pr and Vagc in alook-up table in the processor.
5. Reduce test signal level by approximately 1.0 dB
6. If AGC voltage changes, go to step 3. If no change, end calibration and return to normal reception.
7. To measure Pr_1 measure AGC voltage and look up in table.
8. Interpolate to determine incoming signal strength.

5.0 SUMMARY OF SIGNAL POWER MEASUREMENT TECHNIQUES

There are at least three ways in which satellite power at the ground station can be measured: Radiometer, calibrated receiver and code correlation variance analysis. Either of the former two can determine signal power to within 0.5 to 1.0 dB accuracy. The latter method has not yet been investigated with GPS in mind. The measurement of received power still leaves many unknowns to be evaluated, such as transmitting antenna gain toward the receiving station, path anomalies, and others, in order to obtain an accurate measure of the transmitted EIRP.

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13. ABSTRACT

The report

Provides description of control segment trade-offs, addressing number and location of master control and monitor stations, upload facility and use of existing capabilities. Describes techniques to process and analyze data to maintain the test conditions.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Control Segment						
Orbit Configuration						
Telecommunications Cost						
Master Control Station						
Satellite Test Center						
Monitor Stations						
Reference Ephemeris Determination						
Ephemeris and Clock Processing & Simulations						
Signal Power Monitoring						